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All correspondence should be addressed to:
Prof. K. S. Weerasekera - Editor-in-Chief, Journal of Engineering Technology
Department of Civil Engineering
Faculty of Engineering Technology
The Open University of Sri Lanka
Nawala, Nugegoda
Sri Lanka
E-mail : kolitaw@yahoo.com Telephone : 0112881433

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From the Editor-in-Chief

It is with great joy and pride the Faculty of Engineering Technology is publishing its inaugural edition of the JET - *Journal of Engineering Technology* at a time where great emphasis is given for university research in the country.

Journal of Engineering Technology is a collection of research articles based on research conducted by staff and students of Faculty of Engineering Technology, OUSL over the recent times. The aim of this journal is providing a platform for the staff and students of the Faculty of Engineering Technology to publish their research and project outcomes which are of quality and value to the scientific community. With this intention *Journal of Engineering Technology* will be published on a regular basis (twice a year).

As the editor-in-chief, I would like to thank all the members of the editorial board, independent reviewers, authors of the research papers and staff of the OUSL press for their valuable contributions and support given to me. Finally, I expect faculty members and students to continue with more research papers with high quality to be submitted to the journal in future for emphasizing its importance and add value to the OUSL research culture.

Optimum Blasting Parameters for Single Shot Blasting in Non Fractured Biotite-Gneiss Rocks of Sri Lanka

H.A.S.I Abeywardana[1], G.G.K.Kodagoda[1], M.N.C Samarawickrama[2*]

[1]Sri Lanka Air Force, Colombo, Sri Lanka
[1]Northshore College of Business & Technology (PVT) Ltd, Colombo 15, Sri Lanka
[2*]Department of Civil Engineering, Open University of Sri Lanka, Nawala, Nugegoda, Sri Lanka

[*]Corresponding Author email: mahesh.samarawickrama@gmail.com , Tele: +94112881479

Abstract - *Sri Lanka is absent of a definite technical criteria for selecting the best set of rock blasting parameters which depend on structural conditions and genesis of local rock masses. Therefore, it is of prime importance to identify the optimum rock blasting parameters for most commonly used rock types in local construction industry.*

This study was focused on biotite gneiss rocks and the most important parameters have been checked through test blasts. The effects of blasting parameters on blasting output and its environmental impacts were analyzed. The blasting output performance was measured using the parameters of Degree of Fragmentation and Rock volume yield. The environmental effects were measured using Airblast overpressure and Ground vibration. An optimum blasting parameter set of a burden size of 1.40 m, stemming length of 1.50 m, and ANFO amount of 800 g/borehole for borehole diameter of 40 mm was identified for single shot blasting in biotite gneiss rock masses. The above optimum blasting parameters perform exceptionally well when the intact rock strength is in the range of 70 MPa to 220 MPa.

Keywords: *Burden size, Stemming length, ANFO, Degree of Fragmentation, Rock volume, Air blast overpressure, Ground vibration*

Nomenclature

GSMB – Geological Survey & Mines Bureau
ANFO - Ammonium Nitrate and Fuel Oil (g)
DOF - Degree of Fragmentation (%)
GV – Ground Vibration (mm/s)
AP – Air blast Overpressure (dB)

1 INTRODUCTION

Sri Lankan open cast mining industry is absent of a definite technical criteria for selecting the best performing rock blasting parameters. Hence it is common to observe in the local mining industry that they utilize the experience of operators and skilled laborers and employ the blasting parameters according to their knowledge and experience, which really is a problem in this industry. This causes unnecessary waste of natural resources, higher production cost, and unexpected hazardous conditions in the environment.

The noise generated due to blasting action, creates health problems and vibration may reduce the lifespan of buildings and other structures which are in the close proximity to the quarries. Hence, the Geological Survey and Mines Bureau (GSMB) has imposed the standard air blast overpressure (AP) of the quarry area to be maintained at a level less than 120 dB and ground vibration (GV) level to be less than 5 mm / s. The generation of fly rocks also puts workers and the people living around the area under extreme danger.

Insufficient blasting produces larger rock boulders, which need even tertiary level blasting stages, incurring extra costs. This will not only result in increasing the cost unnecessarily but also will pave the way to reject many ore bodies (assuming that the particular rock category itself is not fragmenting) thus finally abandoning valuable natural resources.

In order to avoid these problems to a certain extent, there is a necessity in developing the best possible combination of blasting parameters for a particular type of rock mass. This will improve the productivity of metal quarry industry, and also the life standards of workers and people living in the particular quarry area. In addition, byproducts of quarry operation can also be used productively.

The scope of this study is to determine the best performing rock blasting parameters in Sri Lankan biotite gneiss rocks. In this research there were two main objectives to be achieved: First, to analyze the behavior of production output and possible environmental effects that will cause under different blasting parameter conditions for the biotite gneiss rock mass. Secondly, to develop a set of optimum combination of blasting parameters for a particular rock that yield maximum blasting performance level with minimum environmental impacts.

2 SRI LANKAN GEOLOGY AND BLASTING THEORY

2.1 Geology of Sri Lanka

When considering Sri Lankan geology, as depicted in Figure 1 and according to Cooray (1984), metamorphic rocks in Sri Lanka belong to Precambrian age which is one of the most ancient and stable parts of the Earth's crust, belonging to the Indian Shield. Other areas are formed by Mesozoic, Tertiary and Quaternary sedimentary formations. Precambrian rocks are exposed from Negombo to Mankulum. Further, according to Cooray (1994) these Precambrian rocks fall into four main groups viz, Highland Complex, Vijayan Complex, Wanni Complex and Kadugannawa Complex.

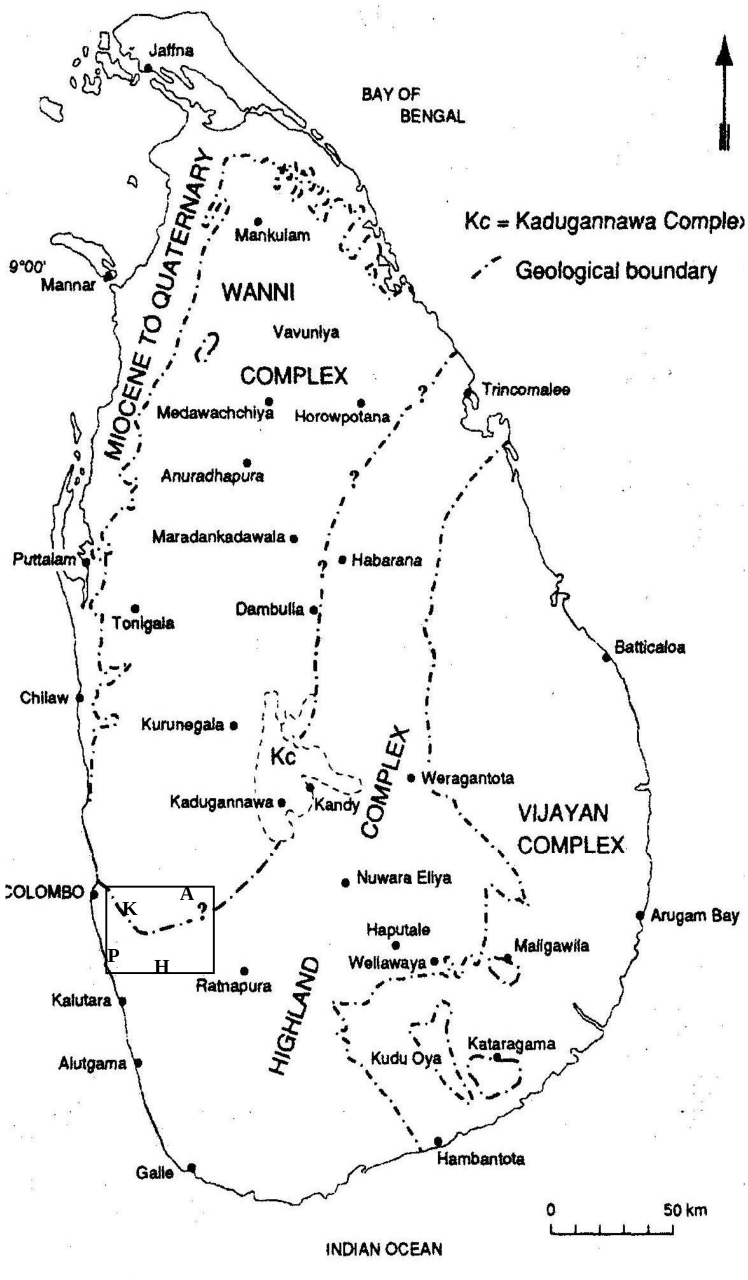
According to Figure 1, the upper boundary of Highland Complex runs across the hill country of Sri Lanka from Colombo - to the north of Trincomalee, whilst its lower boundary begins from Hambantota and runs via Wellavaya to the south of Trincomalee. The formation is made up of garnet-sillimanite gneisses, metaquartzites, marbles, calc-silicate rocks, orthogneisses and charnockitic gneisses (Cooray, 1994).

Vijayan Complex occupies the landward to the east and south-east of the Highland Complex. The rocks of Vijayan Complex consist of granitoids, migmatitic and granitic gneisses, augen gneisses, minor amphibolites and scattered metasediments (Cooray, 1994).

Landward to the west and north-west of the Highland Complex is Wanni Complex. The rocks of this region consist of granitoid gneiss, granitic migmatites, granites and scattered metasediments (Cooray, 1994).

The Kadugannawa Complex lies in between Higland and Wanni Complexes towards central highlands and consist of hornblende, hornblende- biotite and granitoid gneisses.

The rock type considered for this study, the biotite gneiss, belongs to the high grade meta-sedimentary metamorphic rock category. This rock type consists of medium or medium-to coarse-grained gneissic texture having alternative white colored quartz or quartzo-feldspathic bands with dark colored bands mainly consisting of biotite mica.



Legend
A- Avissawella H-Horana P-Panadura K – Kaduwela -Study area

Figure 1 – Map of Different types of geological units of Sri Lanka and the study area

(Source: The Precambrian of Sri Lanka: a historical review (after Cooray, 1994)

2.2 Theory of Rock Blasting

There are a number of theories to explain how rocks are fragmented by explosives. Most popular of them is the reflection theory. When detonating occurs, explosive charge creates a high gas pressure in the blast hole. This generates a compressive strain pulse in the surrounding rock and travels outward in all directions from the center of the hole. Strain pulse decays rapidly with the crushing of the rock in the vicinity of the blast hole. When original compressive strain pulse reaches free surface, reflection tensile strain pulse will generate. The bulk of the rock mass is progressively broken up away from the free faces.

To break the massive rocks, higher blast hole pressure should be provided. Therefore selected explosives should be of maximum strength and detonation velocity. When highly stratified or fissured rocks have to be blasted, the total area of discontinuities is relatively larger than that is created by the blasting. Therefore the explosives of low density and detonation velocity are more efficient. When the detonation of an explosive creates too many fines during the effect of crushing of the rock, it should use Ammonium Nitrate (NH_4NO_3) + Fuel Oil (CH_2) (commonly called as ANFO) mixture and the mixtures of ANFO with inert substances (Carcedo et al., 1995). In Sri Lanka, the mix proportion is 94% of NH_4NO_3 and 6% of CH_2 by weight.

The quantity of explosives necessary to fragment 1 m^3 of rock is known as the powder factor. One Kilogram of explosive can expand to 1,000 litres of gas in milliseconds and released up to 5,000 kJ of heat.

$$3NH_4NO_3 + CH_2 \rightarrow 7H_2O + 3N_2 + CO_2 + \text{Heat}$$

2.3 Common Rock Blasting Parameters

Commonly used rock blasting parameters are given in the Figure 2. When deciding the blast hole diameter, explosives can be most effectively utilized by using a burden of approximately 40 times the blast hole diameter. When the blast hole diameter is increased, the burden gets reached to the bench height and explosion becomes less efficient (Hoek & Bray, 1981). The use of large diameter blast holes also increases the fly rock and air blast problems and can give rise to excessive fracturing of the remaining rock mass.

Practically, if the effective burden is too small, the radial cracks will propagate to the free face easily and will allow the explosion gasses to come out. This causes the loss of efficiency and the generation of fly rock and air blast problems. Too large burden will result in poor fragmentation and a loss of efficiency in the blast. Also, the burden distance should be less than the hole depth, to prevent surface fracturing. The burden distance (B) is calculated using Andersen's formula for single holes given by $B = C \sqrt{(DL)}$, where, D is the blast hole diameter, L is the length of the hole and C is a constant (Carcedo et al., 1995).

When choosing the effective spacing, too small spacing causes excessive crushing between charges and on the surface crater breakage, large blocks in front of the blast holes and toe problems and an irregular face over hanging in the new bench. Experience suggests that an effective spacing of 1.25 times the effective burden gives good results (Carcedo et al., 1995).

Stemming length can vary between 0.67-2 times the burden width. But this depends on the properties of the rock. Too little stemming causes the explosion gases to come out and generate fly rocks and reduction in the effectiveness of the blast. Too much stemming causes poor fragmentation of the rock above the top load. Stemming columns shorter than two thirds of the burden width, normally causes fly rock and back break problem (Carcedo et al., 1995).

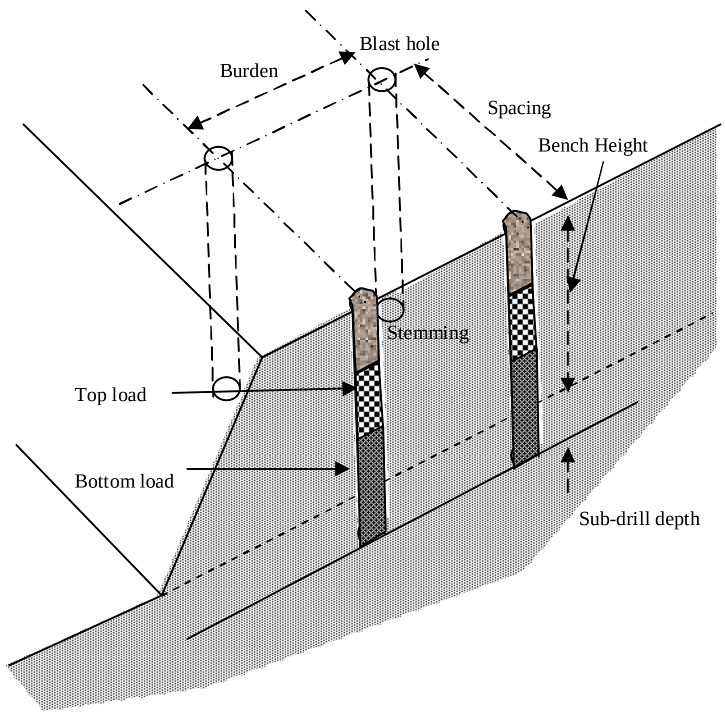


Figure 2 - Definition of bench blasting terms

Sub drilling or drilling to a depth below the toe of the bench is in order to break the rock on the floor of the bench, so that a shovel can dig into the required level. If there is poor fragmentation at this level, it can lead to very expensive shovel operations which cause delays and break downs. Excessive fragmentation shows that the rock forming the lower bench is damaged and will reduce its stability. Experience has shown that a Sub drilling depth of 0.2 to 0.3 times the distance between adjacent blast holes is usually adequate to ensure effective digging to bench grade (Carcedo et al., 1995).

2.4 Fragmentation of Rocks

When a solid mass of rock is broken by explosives, the size of distribution of rock boulders and particles produced are termed as Fragmentation. When poor fragmentation occurs, it needs secondary blasting operation to reduce the over size or large boulders. Then it can be handled economically, safely and efficiently by loading and haulage equipment. Excessive fragmentation of rock mass indicates possible wastage of explosives.

In order to improve the fragmentation, measures such as reduction of hole depth. (shallow holes with improved distribution of explosives), reduction of spacing between adjacent holes in a row, reduction of burden distance, use of an explosive with greater gas generation (have) and less brisance and using short delay detonators can be adopted.

3 METHODOLOGY

In this study, twenty (20) number of test blasts were carried out under the guidance of GSMB in the selected area.

3.1 Selection of the Study Area and Rock type

When analyzing the total rock aggregate consumption of Sri Lanka, the highest level of rock aggregate demand is in Western province. Considering this fact and the type of rock focused in this study, the quarrying operations are presently carried out in the Biotite gneissic rocks in Kaduwela, Panadura, Horana and Avissawella areas. Therefore, this study was restricted to the quarries located in the above areas. These locations are shown in the above Figure (figure 1) and as depicted in the map, geologically these belong to both Highland and Wanni Complexes and are located close to the boundary which separate these two Complexes.

3.2 General Assumptions Made

When going through the theory of rock blasting and structural properties of rocks it is quite a Complex task in developing a generalized combination of best performing blasting parameters suitable for every rock mass and for each and every blasting parameter. Therefore this study was conducted and results were analyzed while keeping following blasting parameter factors constant.

1. Blast hole Diameter is 40mm and the packing factor is equal to 1.
2. Sub-drill depth is zero.
3. Blast hole inclination is vertical.
4. No effective spacing between holes since the test blasts were carried out for single shot holes only.
5. Rock mass is absent of fractures and the spacing between fracture planes is high.
6. Fly rock condition is absent.

3.3 Rock Blasting Parameter Measurements

Throughout the study, the performances (production performance) of test blasts were measured under different blasting parameter conditions (burden size (m), stemming length (m) and amount of explosives used (ANFO) (g)) and intact rock conditions (UCS value in MPa).

3.4 Production Performance Measurements

Keeping the above parameters constant, the performance of each test blast was analyzed in two folded criteria, viz., production performance and environmental impact performance. The production performance was measured using; Volume of rock yield (m^3) and Degree of Fragmentation (%).

The rock volume produced after each test blast was measured by tightly packing the aggregates on a flat area in a cubical arrangement. The plan area dimensions of this arrangement were always maintained as 4.0 m X 2.0 m.

The degree of fragmentation (DOF) was measured using following Equation;

$$DOF = \frac{\text{Total Volume Yield due to blasting } (m^3) - \text{Total Volume of rock boulders which does have dimensions greater than 0.61 m } (m^3)}{\text{Total Volume Yield due to blasting } (m^3)} \times 100\ (\%)$$

The environmental impact performance was measured using; Ground Vibration (GV) and the Air blast Overpressure (AP). These were measured using BLASTMETER instrument provided by the GSMB. The performance for above two parameters were checked against GSMB imposed threshold limits values of Ground vibration level which should be less than 5 mm/s and Air blast overpressure which should be less than 120 dB.

3.4 In-tact Rock Mass Characteristics

The only rock mass character that was considered in this study was the intact strength of rock mass, which is the unconfined compressive strength (MPa). This was by collecting blasted rock samples from respective locations and performing point load test at the laboratory and converting the results to obtain uniaxial compressive strength by empirical equations.

3.5 Analysis of Performance of Test Blast

For the analysis of performance of test blasts under various blasting parametric and intact rock strength conditions, the data were tabulated and blasting performance graphs were plotted against each blasting parameter and for intact rock conditions.

4 RESULTS AND ANALYSIS

Table 1 given below provides the summary of the results of 20 numbers of test blasts carried out in this study.

Table 1: Results from blasting operations

Test Blast Reference Number	Burden (m)	Stemming(m)	Strength (MPa)	ANFO (g)	Volume (m^3)	GV (mm/s)	AP (dB)	DOF (%)
1	0.600	0.900	118.15	320	4.9	1.27	112.8	45
2	0.650	0.780	148.72	160	5.0	1.40	88.0	45
3	0.800	1.200	156.19	265	5.2	1.52	110.2	47
4	0.800	1.100	160.25	280	5.2	0.13	109.9	48
5	0.900	0.750	223.56	215	4.7	0.33	102.8	50
6	0.900	1.100	143.96	330	7.5	0.13	110.9	55
7	0.900	1.300	193.49	280	5.2	0.13	88.0	45
8	1.000	1.500	103.90	290	5.5	0.33	101.9	48
9	1.100	1.200	170.32	265	5.0	0.38	108.4	60
10	1.100	1.400	206.17	410	8.8	0.27	112.7	57
11	1.100	1.000	84.76	415	8.5	1.12	109.3	55
12	1.100	1.200	117.83	375	8.5	0.13	113.3	60
13	1.200	0.950	142.10	200	4.9	0.13	101.0	50
14	1.200	1.500	230.30	260	4.9	1.14	114.8	52
15	1.300	2.700	71.14	900	9.9	0.13	109.9	62
16	1.500	2.300	227.93	1500	8.7	2.62	113.6	61
17	1.600	2.200	206.17	1500	8.8	5.12	114.9	60
18	1.700	1.900	124.92	2490	10.2	3.05	115.6	65
19	1.800	2.100	169.19	1500	9.5	1.75	114.2	63
20	1.900	1.100	152.58	290	5.7	0.13	107.0	52

In Figure 3, the AP increases with the amount of ANFO used. This reaches to a peak level of 117 dB with 1.60 kg of ANFO. AP is continuously increasing with the burden size in Figure 4 and reaches the value of 113 dB when having a burden of 1.70 m. As it can be expected, Figure 5 depicts that AP increases with the stemming height and the maximum is 113 dB with a stemming height of 2.00 m. Further, AP decreases after achieving a maximum at 2.00 m stemming height. According to Figure 6, the AP values decrease with the increasing in-tact rock strength, reaches a minimum of 106 dB at 150 MPa and again increases with the increasing in-tact rock strength.

In Figure 7, the DOF increases with the amount of ANFO and reaches to a peak level of 65% with 2.00 kg of ANFO. Again, DOF increases with the burden size as shown in Figure 8 and reaches a maximum of 60% when having a burden of 1.70 m. As it can be expected, in Figure 9 DOF decreases with the increasing in-tact rock strength reaches a minimum of 51% at around 170 MPa and again increases with the increasing in-tact rock strength. The DOF is continuously increasing with the increasing stemming height as depicted in Figure 10.

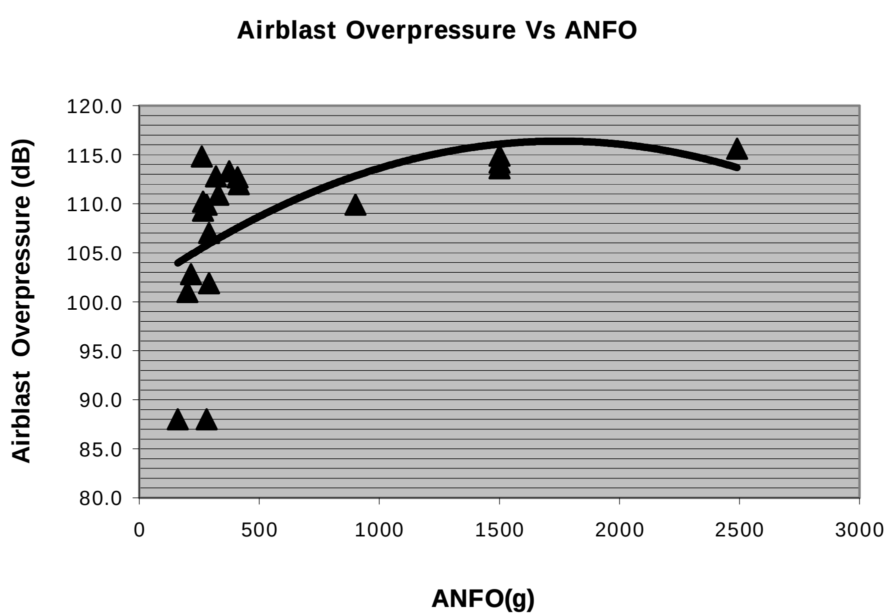


Figure 3 – Variation of Airblast Overpressure with the amount of ANFO

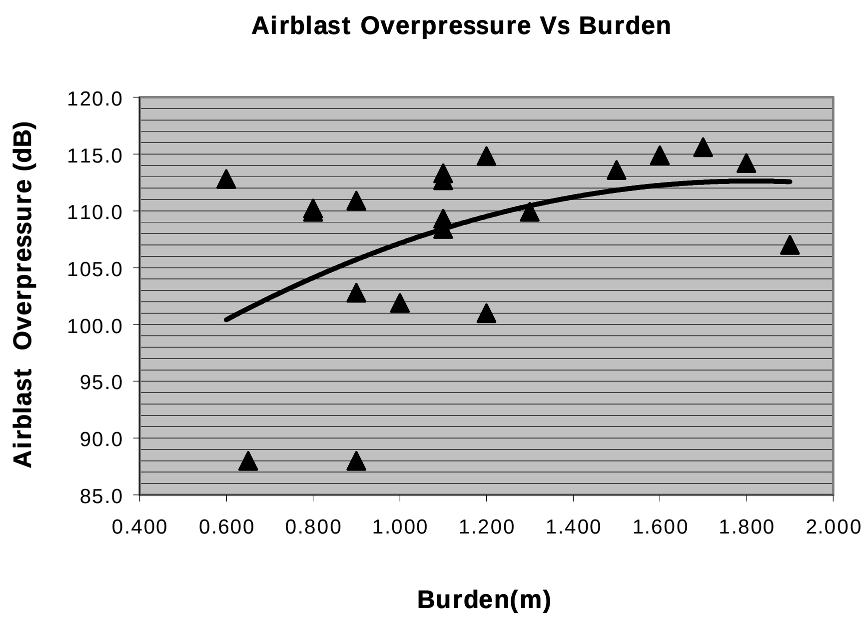


Figure 4 – Variation of Airblast Overpressure with the Burden size

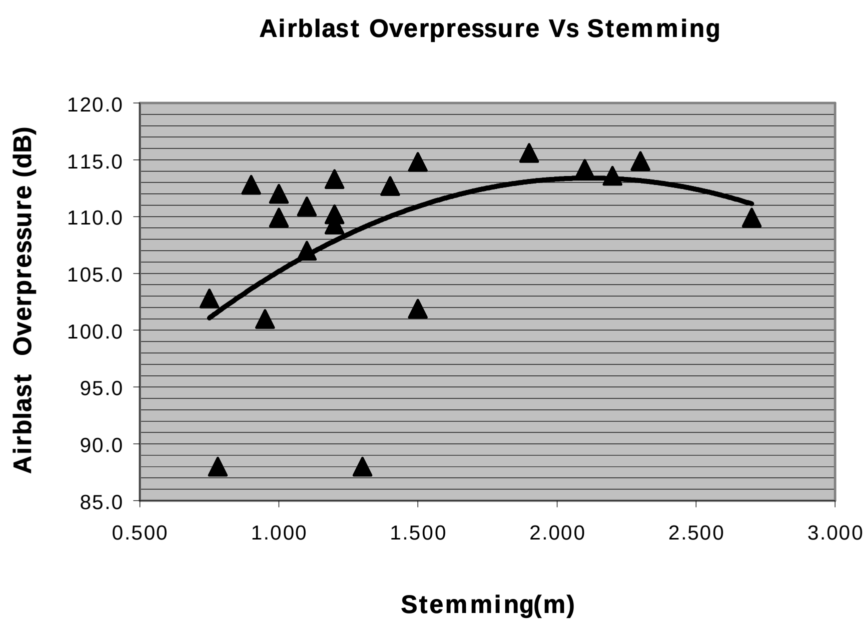


Figure 5 – Variation of Airblast Overpressure with the Stemming length

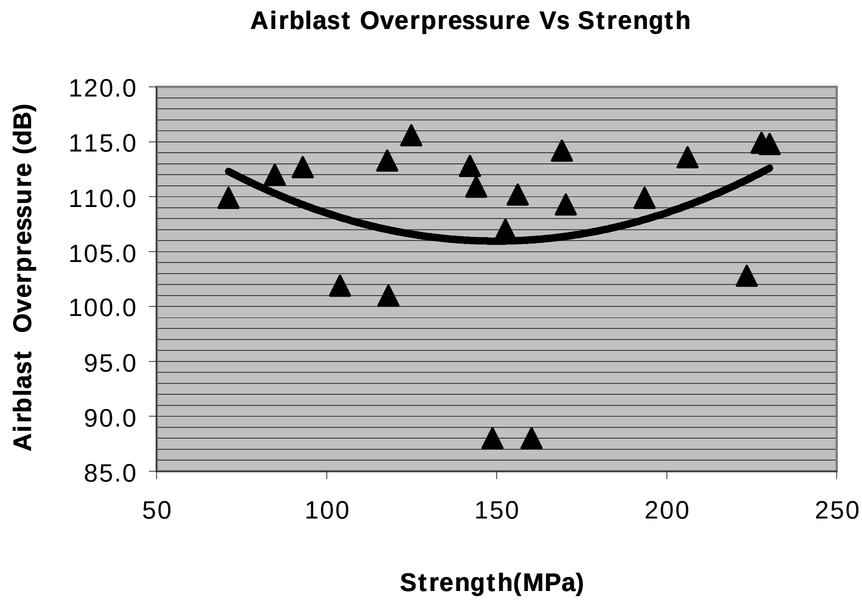


Figure 6 – Variation of Airblast Overpressure with the In-tact rock strength

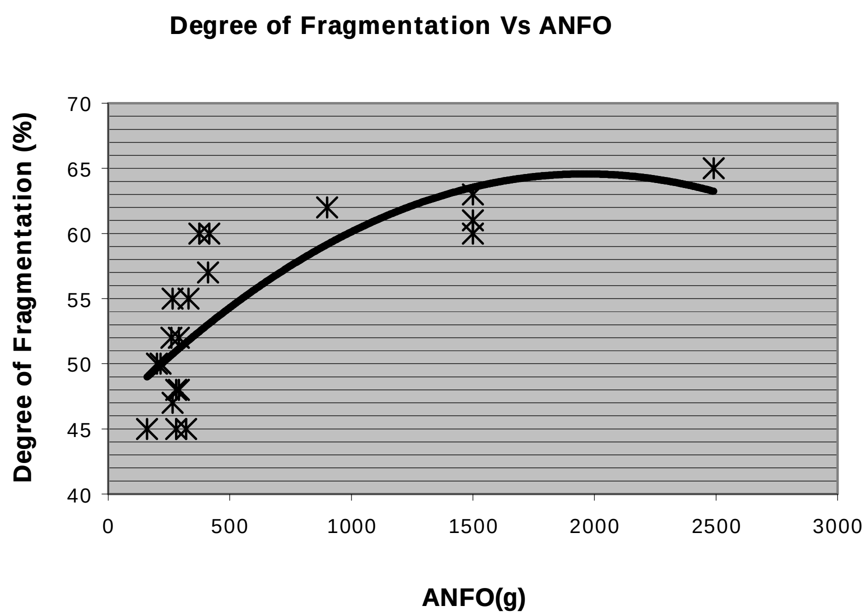


Figure 7 – Variation of Degree of fragmentation with the amount of ANFO

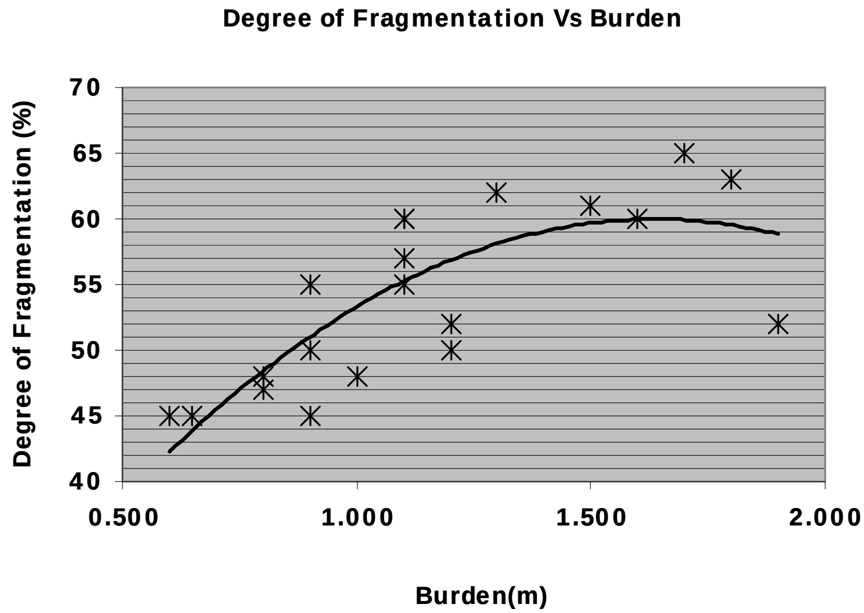


Figure 8 – Variation of Degree of fragmentation with the Burden size

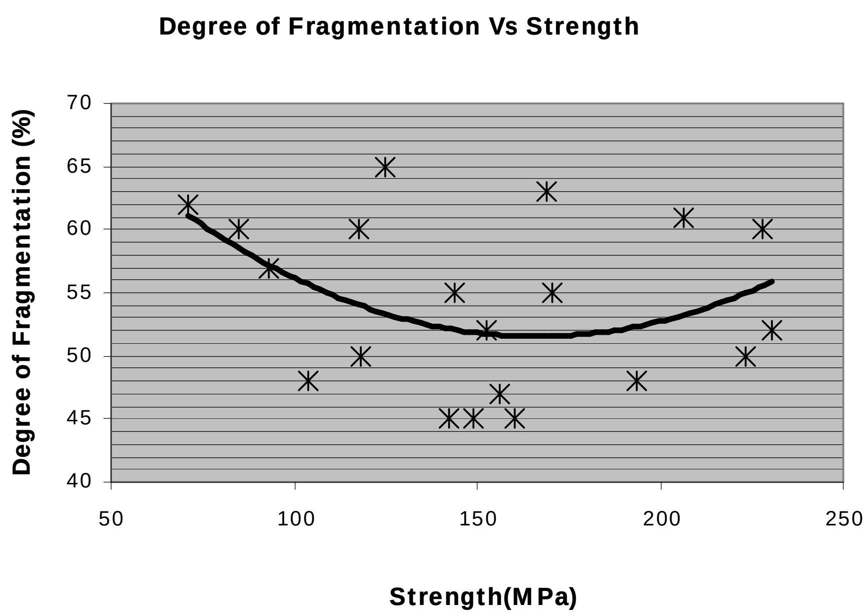


Figure 9– Variation of Degree of fragmentation with the In-tact rock strength

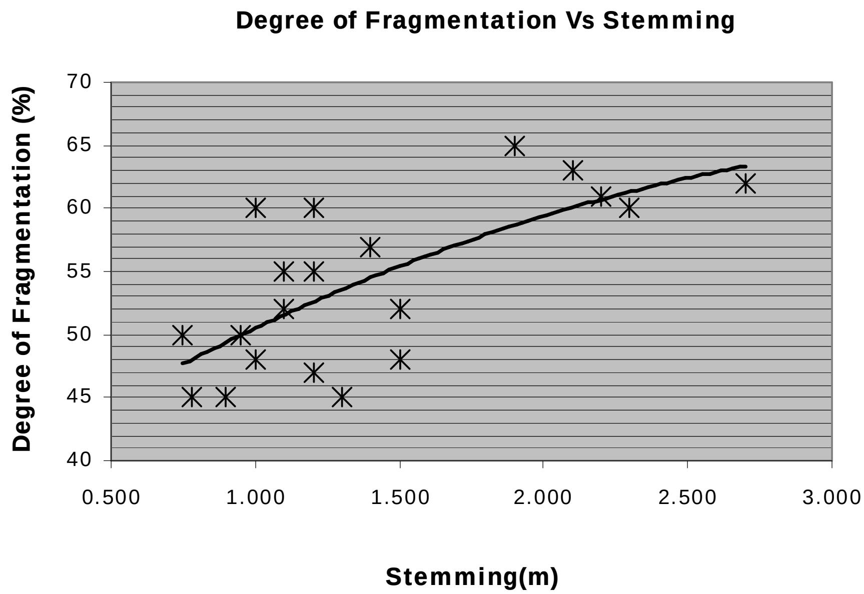


Figure 10 – Variation of Degree of fragmentation with the Stemming length

According to Figures 11, 12 13 and 14, the GV values are continuously increasing with the increasing burden size, ANFO amounts, stemming height and intact rock strength.

Maximum rock volume of 10.00 m^3 is achieved with an ANFO weight of 1.80 kg. As depicted in Figure 15, the yielded rock volume increases with the amount of ANFO used and reaches to a maximum and then decreases with further increase in ANFO levels. Volume of rock that yields in a blast is increasing with the burden size as depicted in Figure 16 and reaches to a maximum value of 8.40 m^3 when having a burden of 1.70 m. In Figure 17, the yielded rock volume is continuously increasing with the stemming height. According to Figure 18, the rock volume yield decreases with the increasing in-tact rock strength reaches a minimum of 6.00 m^3 at 180 MPa and again increases with the increasing in-tact rock strength.

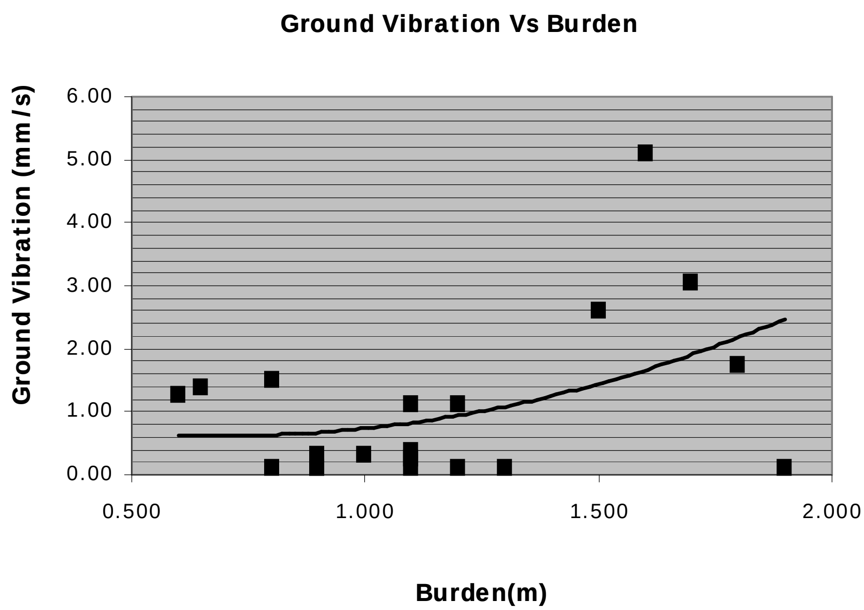


Figure 11 – Variation of Ground vibration with the Burden size

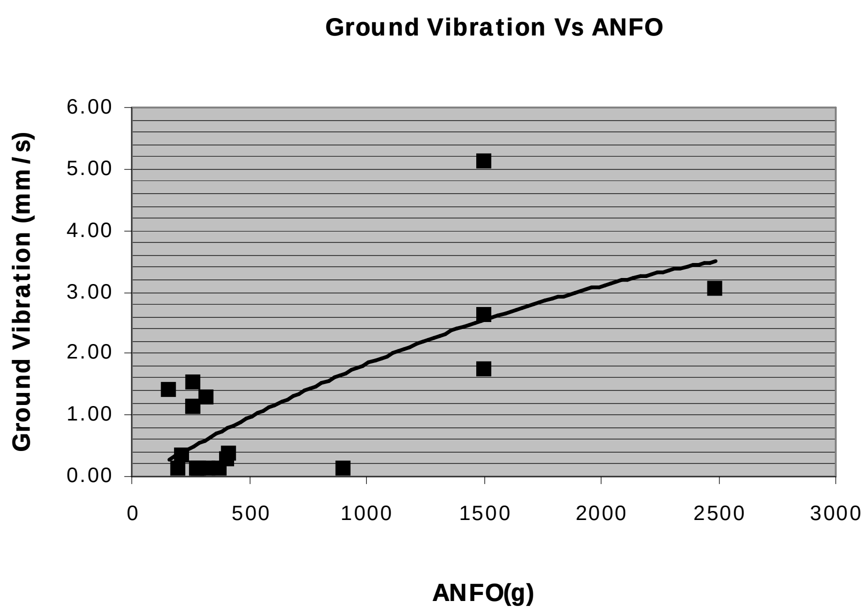


Figure 12 – Variation of Ground vibration with the amount of ANFO

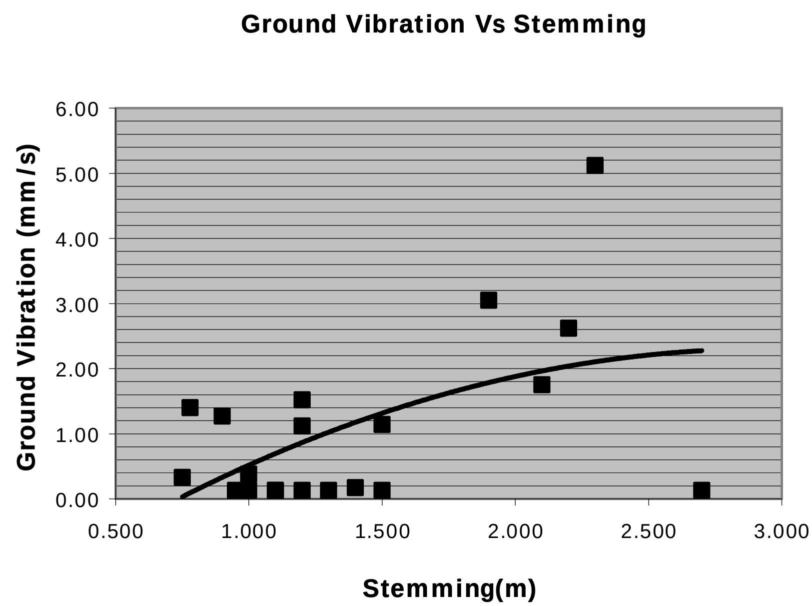


Figure 13 – Variation of Ground vibration with the Stemming length

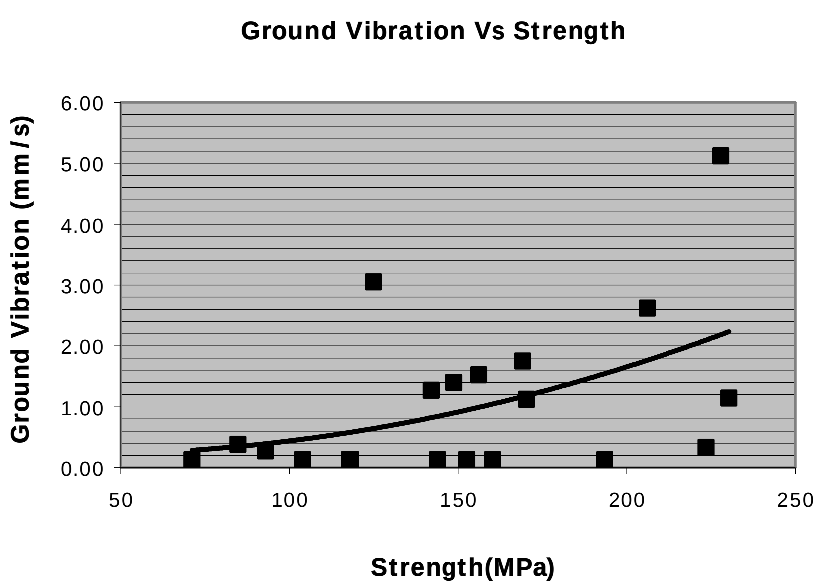


Figure 14 – Variation of Ground vibration with the In-tact rock strength

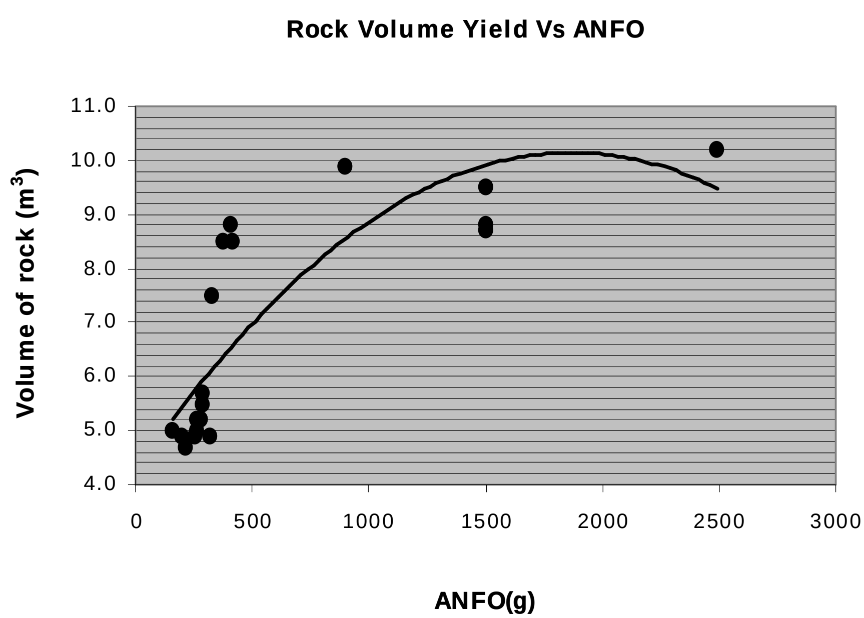


Figure 15 – Variation of Volume of rock yield with the amount of ANFO

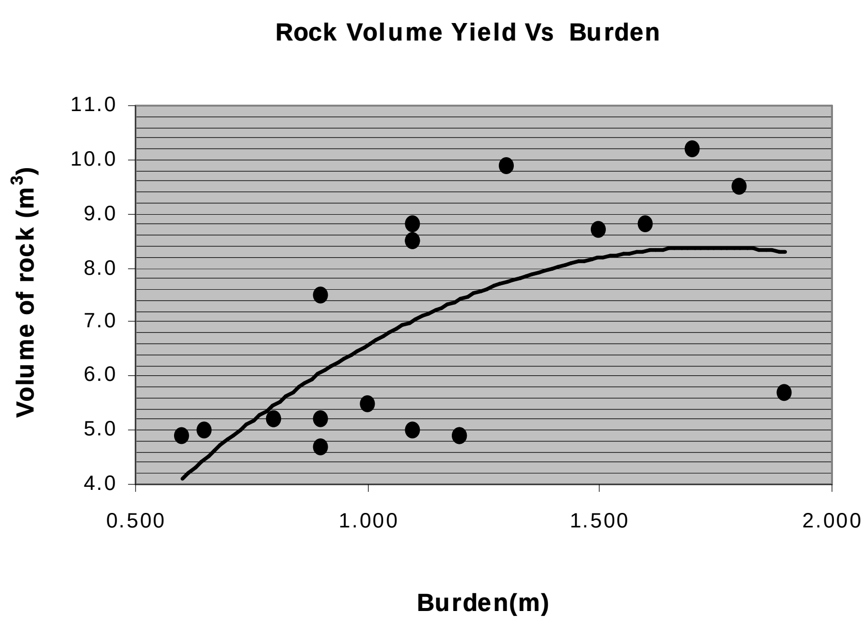


Figure 16 – Variation of Volume of rock yield with the Burden size

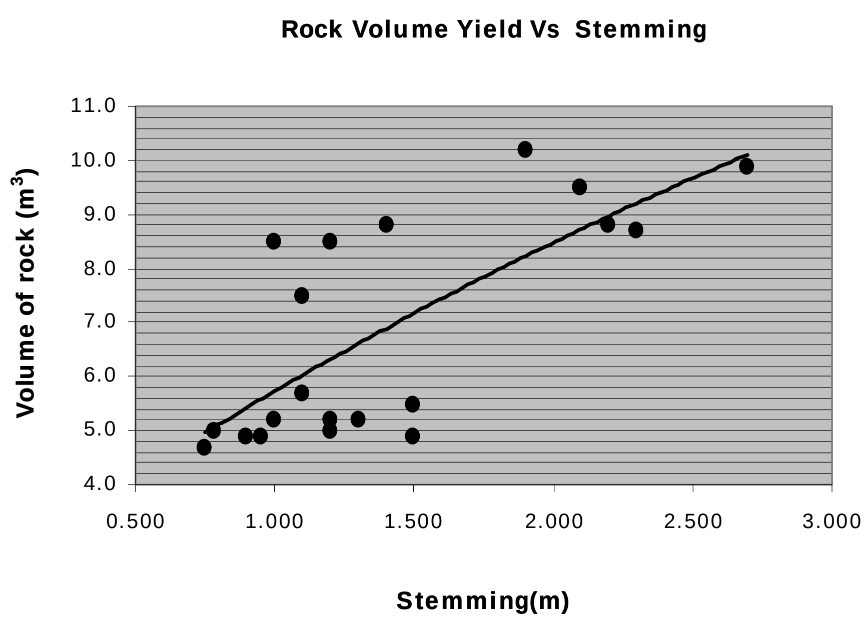


Figure 17 – Variation of Volume of rock yield with the Stemming length

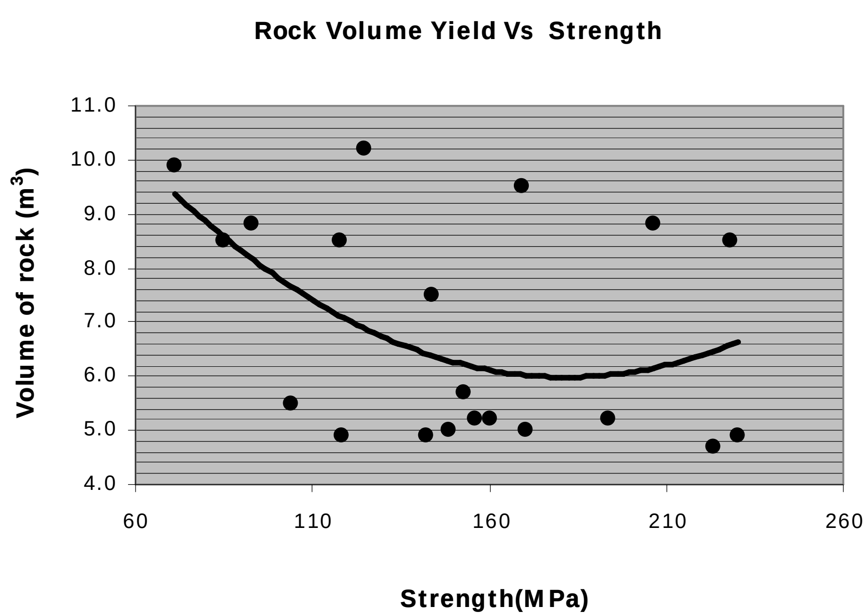


Figure 18 – Variation of Volume of rock yield with the In-tact rock strength

5 DISCUSSION.

Theoretically, the above results are in agreement with the classical rock blasting practices. When higher amounts of explosives are used, enormous pressure generates inside the borehole, which creates and ejects excessive air blast overpressure to the air when it is released from the borehole. The AP reaches the vulnerable range of 110 dB to 120 dB when more than 800 g of ANFO is used. A burden size more than 1.40 m will create the AP to move into the vulnerable limits and the same will create when the stemming height is more than 1.50 m. AP exceeds 110 dB when the trough oriented AP – intact rock strength curve is below 70 MPa and above 220 Mpa. However, the data are highly scattered and most probably this is due to other intact rock conditions such as variations in mineralogical compositions and texture.

Even though a higher degree of fragmentation can be achieved with 2.00 kg of explosives, it will create AP to push into vulnerable limits and when considering this factor, the DOF that can be achieved will limit to 58% which is corresponding to 800 g of ANFO. The burden size which is restricted from AP limits (which is 1.40m) results in a DOF of 58%. However, when the stemming height is increased excessive AP is generated and the DOF is limited due to this excessive AP and the safe stemming height of 1.50 m results in 55% DOF. When applying the safe limit criteria of the above AP to intact rock strength (i.e in between 70 MPa – 220 MPa), a DOF of 61% and 53% can be achieved at its lower and upper bounded values respectively. Again in this case also the data in the intact rock strength plot are highly scattered and the reasons are same as in the AP variation.

When applying a blasting parameter set of 800 g of ANFO, 1.40 m of burden size and a stemming height of 1.50m to ground vibration plots, GV values always exit below 2 mm/s, which is quite safe when considering its threshold limit of 5 mm/s.

With the application of 800 g ANFO limit, a maximum rock volume of 8.00 m^3 can be achieved, while 1.40 m of burden size will yield 8.00 m^3 again. A rock volume of 7.20 m^3 will yield with the use of 1.50 m of stemming height. The safe intact rock strength region will produce a rock volume of 9.40 m^3 and its lower limit and 6.40 m^3 at the upper limit.

6 CONCLUSIONS

In addressing the main objectives of this study, following conclusions can be made.

6.1 Impact of Blasting Parameters on Production output and Environmental effects

1. A maximum rock volume of 10.00 m^3 can be achieved with 2.00 kg of ANFO. Further increase of ANFO will result in the decrease of yielded rock volume. However, this value is limited to 8.40 m^3 with a maximum burden size of 1.70 m. The increasing stemming height continuously increases the yield and the corresponding height at the maximum yield is 2.70 m.

2. The degree of fragmentation increases with ANFO levels and reaches the maximum of 65% with 2.00 kg of ANFO and further addition of ANFO will result in the

3. This maximum value of DOF is limited by the effects of burden size and reduces its value to 51% with a burden size of 1.70 m. The same maximum degree of fragmentation of 51%

can be achieved with intact rock strength of 170 MPa. The rising stemming height continuously increases the yield and the corresponding stemming height at the maximum DOF, is 2.70 m.

4. The air blast overpressure values increase with the increasing ANFO levels and this trend is the same for burden size. With the increasing stemming height, the AP increases and it reaches to a maximum of 113 dB with a stemming height of 2.00 m and further addition of ANFO will reduce the airblast overpressure. The airblast overpressure decreases with the increasing intact rock strength, reaches to a minimum of 106 dB at 150 MPa and increases thereafter.

5. The ground vibration levels increase with the rising values of all blasting parameters and also with the intact rock strength.

6. When considering the maximum production output view, from the above conclusions, it can be proposed to use 2.00 kg of ANFO with a burden size of 1.70 m. A stemming height of 2.70 m will produce a rock yield volume of 8.40 m^3 with a degree of fragmentation of at least 51% from a rock mass with intact rock strength of 170 MPa. These parametric conditions will cause environmental hazards. Therefore, these blasting parameters can be effectively utilized in isolated quarry areas.

6.2 Optimum Set of Blasting Parameters for Minimum Environmental Impacts that Produces Maximum Production Output

1. The safe allowable airblast overpressure imposed by GSMB is 110 dB. To meet this requirement, a weight less than 800 g of ANFO should be used. Also, a burden size less than 1.40 m should be adopted to mitigate AP problems. The stemming height should be maintained less than 1.50 m (not too small, which again cause to AP problems). AP exceeds safety limits when the intact rock strength is below 70 MPa and above 220 Mpa.

2. When considering the above mentioned parameters in (1), the maximum degree of fragmentation that can be achieved under safe AP conditions is 55% and the maximum rock volume that can be obtained is limited to 7.20 m^3.

3. The above set of blasting parameters firmly fits to the safe ground vibration levels which always exits below 2 mm/s and is quite safe when considering its threshold limit of 5 mm/s.

7 FURTHER RECOMMENDATIONS

This study was focused to make a base to develop a set of blasting parameters that will suit best for a given rock type. However, due to various constraints, impact of other blasting parameters and intact rock conditions on blasting performance was unable to investigate. Further, in this study the impact on Fly rocks was also not performed as blasting operations were carried out under restricted conditions. Hence it is highly recommended to use these parameters in the industry with a sense in the impact from other non investigated parameters also.

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Soft Skills Competency among OUSL Graduates-Employers' Perspective

D.A.R. Dolage[1] and C.N. Hearth[2]

[1] Department of Civil Engineering, The Open University of Sri Lanka, Nawala, Nugegoda, Sri Lanka

[2] Department of Textile and Apparel Technology, The Open University of Sri Lanka, Nawala, Nugegoda, Sri Lanka

Corresponding Author: dadol@ou.ac.lk, Tele: +94112881289

Abstract - *This study investigates into the soft skill requirement of graduates seeking employment, according to the perspectives of four types of stakeholders namely, employers, academics, graduates and current students. Eighteen soft skill types were identified and ranked according to their importance based on the mean Relative Importance Indexes (RII) computed for each soft skill type. Based on this, five most important soft skills were identified namely, Interpersonal (0.869), Leadership (0.864), Oral Communication (0.862), Decision making (0.850), and Team work (0.850). Relative Competence Indexes (RCIs) were computed for OUSL, 'other local' and foreign graduates according to the perceptions of the stakeholders of the OUSL. It was found that OUSL graduates perform poorly in relation to all the core soft skill dimensions, compared to the other two types of graduates.*

Key words; Employment competencies, Graduate employment, Soft skills, Technical skills

1 INTRODUCTION

The acquisition of soft skills by a graduate of any discipline has become indispensable in the highly competitive global market, where the workplace is increasingly becoming interpersonal. This relatively new requirement of soft skill competency for career progression is gathering momentum unprecedentedly. The companies are keen to assess the knowledge, skills and abilities (KSAs) of the applicants in a bid to select the most fitting candidate for their company. The majority of companies judge the knowledge by measuring the Intelligent Quotient of the candidate. The companies are not keen to asses the technical knowledge which is to a greater extent fulfilled by the persuasive evidence of formal academic qualifications. Any specific technical skills required for a company can be easily provided through training since the candidate is equipped with the fundamental technical skills. Nonetheless, the employers would want their future managers / executives to possess adequate levels of soft skills.

Kramer (2011) provided robust definitions for hard skills and soft skills as follows:
Hard skills are the skills needed to effectively complete job tasks such as computing or machinery. They are often acquired through technical training or job preparation courses. Soft sills are the skills useful to execute the hard skills. They are the professional aptitudes that correspond with one's personality and behaviour. They include creativity, communication, problem solving, critical thinking, leadership and teamwork. According to a study by Muir (2004), soft skills such as social intelligence, collaboration, communication, listening, and novel and adaptive thinking are the critical skills that employees will need to find success in the workplace (Ketter, 2011). The objectives of this study are:

1. To identify and rank the important soft skills needed by the graduates seeking employment in the industry.

2. To evaluate and compare the level of soft skills competence among graduates based on the type of degree awarded.

2 LITERATURE REVIEW

2.1 Graduate Unemployment in Sri Lanka

The current primary and secondary education enrolment rates of Sri Lanka are 98% and 97% respectively, which are quite high for a developing economy. Chandrasiri (2008) ascribed this to the strategic public policy decisions taken by Sri Lankan policy makers in the 1940s to make significant investments in education and other social sectors. There are 18 state universities in Sri Lanka with an annual intake of about 22,000 students per year and the annual graduate output is around 20,000 per annum.

Over the past three decades, unemployment of graduates, with demand side problems not being addressed, has escalated into a major social, political and economic problem in Sri Lanka. In 2005, there were 40,527 unemployed graduates who sought entry to Graduate Placement Scheme (Chandrasiri, 2008).

Karunaratne (2010) points out, although universities are not meant to train graduates as in the vocational schools, certain basic attributes were lacking in the graduates, some of them being (a) lack of commitment and earnestness (b) inability to establish good relations with superiors, peers and subordinate grades (c) inadequate or lack of knowledge of English required for the job (d) insufficient familiarity with modern day technology (e) lack of enthusiasm for retraining. On account of these shortcomings, current graduates are not attractive to the privates sector whose motive, naturally, is profit making and such graduates were considered a burden.

2.2 Changing needs of private sector Labour market

It is time the students and teachers realize that they must demonstrate proper behaviour to the public and to the potential employers in order to change the present attitude of the employers and public towards the university students and graduates. The graduates should be mindful that they are in a world of advancing technologies and processes. The knowledge gained is fast becoming obsolete and the necessity of acquiring new knowledge must be recognized. Regarding, graduate unemployment, Weerakkody (2010) provides three plausible hypothesis:

i) the prevalence of a skills mismatch where the education system is not providing what the labour market needs.

ii) public sector employment and wage policies operating in the country lead to a queuing behaviour among the population for the attractive jobs.

iii) existence of stringent labour market regulation prevents employment creation in the private sector.

Weerakkody (2010) reports that many studies have revealed that in general, university graduates lack basic skills sought by employers like 'speak and write' with impact, adaptability, self confidence and basic commercial knowledge.

Karunaratne (2010) says in a highly competitive world, another method for success is the acquisition of multiple skills. This emanates from the private sector employers' preference to recruit graduates who have acquired professional qualifications outside the discipline in which they have majored for the degree, eg. some engineering graduates acquiring professional qualification in other disciplines such as accountancy, management, computing and marketing.

Indraratna (2010) says private sector enterprises keep on complaining that the graduates coming from the non professional faculties of our universities are not suitable for them. They have been very slow in revising and upgrading their curricula and courses to suit the competing demands of a knowledge-based global economy.

2.3 Recent initiatives by state and private sector to improve soft skills

In 2011, the Ministry of Higher Education launched a programme for the first time to introduce soft skills along with English and ICT skills to those who had been selected to state universities. This is an ongoing programme conducted in collaboration with the Ministry of Defense and will be conducted at Military camps.

The World Bank project 'Higher Education for the Twenty First Century (HETC)' has different components each committed to improve certain aspects of higher education. One component, the University Development Grant (UDG) is aiming to improve is the social and economic relevance of university education and thereby to make graduates more employable. This task is to be accomplished through the following four activities:

i) Enhancing ICT skills of students
ii) Improving English language skills of students
iii) Strengthening Soft Skills of students
iv) Promoting Ethnic Cohesion among students and staff

The 18 universities and institutes eligible for the grant have proposed to implement the activity of 'Strengthening Soft Skills of students' either as a stand alone subject or by incorporating soft skills components into the existing subjects. Three instances where state sector universities have attempted to market their students are described below:

The Faculty of Engineering of the University of Moratuwa annually organizes a 'Careers Day' in collaboration with the Career Guidance Unit and the Student Association. About thirty organizations from conglomerates, banks and large private sector companies participate on this day to inform the students who have just sat the final year examination, of their selection criteria, skill requirements etc.

The Faculty of Engineering of the University of Peradeniya annually organizes an 'Industry day' (Efi 2012) with the participation of both public and private sector organizations involved in engineering, utilities and other services. On this day, these organizations can interview and select the final year undergraduates who are ready to join the industry in June 2012.

The Faculty of Management of the University of Sri Jayewardenepura conducts lectures in the evening and expects students to work in the private sector at least for short stints to gain some training. The private sector commitment to provide such short term assignments with a monthly stipend to students shows that they welcome the idea of pre degree training.

The above examples show that the prevailing trend among state sector universities to market their graduates is a harbinger to the introduction of soft skills to the undergraduates. Such early exposure to working environment will enthuse students to acquire soft skills. Providing such training in soft skills and state universities becoming more market oriented can guarantee a good future for our graduates.

2.4 Importance and types of soft skills

Wijesingha (2010) says the country has to recognize that education means not just academic learning, but also the development of professional and vocational skills, and the soft skills that will allow these too to be used productively. Ample evidence can be adduced from the industry to prove that those workers who progress swiftly in employment have both excellent technical skills and soft skills. According to Drucker (1994), the decline of manufacturing has created a 'knowledge worker' class, which he estimated to be a third of the American labour force at the end of the 20^{th} century. Muir (2004) says the effective knowledge worker works in teams, multitasks, and is a critical and creative thinker. Such a worker must adapt well to social and operational contexts. Hence, competence in soft skills which are attitudes and behaviours displayed in interactions among individuals that affect the intended outcomes is a 'must-have' in the present day context.

Owing to the competence in hard skills graduates can directly enter the path to leadership. Hence, it is worthwhile to explore what skills can guarantee their path to leadership without faltering. It is difficult to coin a single definition for Leadership, akin to most of the other management concepts. According to Cole (2011), leadership has been defined in terms of individual personalities, leader behaviour, role relationships, follower perceptions, influence over others, influence on tasks/goals etc. Nonetheless, according to most definitions, leadership entails a primary concern to motivate a collective group of individuals to work together to achieve a common objective while alleviating any conflicts that may arise during their trek towards that objective. Cole (2011) says the leader required to be adept at soft skills, commonly known as interpersonal or social skills. The author recommends five soft skills every leader should practice: sensitization to follower expectations, inspiring others, building positive effects, communicate and listen and individuation.

It is observed that different authors adopt different types of soft skills in their studies to measure the degree of soft skills competence. Weber *et al*, (2009) adopts 101 very basic level soft skills to measure soft skill competence among entry level managers in the hospitality sector. Nyman (2006) explained five types of skills in his study on soft skills of engineers, namely Ambiguity, Relationship building, Decision making, Executive presence and Humor. Kramer (2011) having said that soft skills are used to execute the hard skills, describes soft skills are the professional aptitudes that correspond with one's personality and behaviour. They include creativity, communication, problem solving, critical thinking, leadership, and team work.

Balaji and Somashekar (2009) in their study on 'comparative study of soft skills among engineers', Identified14 soft skills necessary for being successful, which are Leadership, Team work, interpersonal, Problem solving, Creativity/innovation, Written Communication, Oral Communication, Flexibility, Presentation, Continuous Learning, Futuristic thinking, Decision making, Self management and Listening.

Ketter (2011) says soft skills are 'must-haves' in future workplace and identifies key soft skill types namely, social intelligence, collaboration, communication, listening, and novel and adaptive thinking, which employees will need to succeed in the workplace.

The selection of soft skills needed for a particular profession depends on the nature of the profession and the culture (Ketter, 2011). The types of important skills could be numerous and training in these could be tedious and time taking. Hence, when training of staff, it is important to identify a few most important types to simplify the task. The following is a description of the 18 soft skills selected for the study of which nine skills had been included in the study by Balaji and Somashekar (2009).

Leadership
Leadership is the factor that influences, motivates and challenges the membership to achieve the predetermined goals. Leadership enhances adaptability to a variety of situations and circumstances.

Time management
Time management is the act or process of planning and exercising conscious control over the amount of time spent on specific activities, especially to increase effectiveness, efficiency or productivity. Time management may be aided by a range of skills, tools,

and techniques used to manage time when accomplishing specific tasks, projects and goals complying with a due date.

Stress management

Stress management skill helps to plan your work in the workplace well and not letting it overwhelm you. This also helps you to feel that you are in control of your life and you are capable of making things go smoothly. The productivity of workers, adept at this skill, is high and prolonged mismanaged stress can make you feel sick and leads to low productivity.

Team work

Team work encourages members and facilitates cooperation, instills a sense of pride, trust and group identity. It fosters commitment, team spirit and helps the teams to achieve their goals.

Negotiation

This skill effect a process by which the involved parties or groups resolve matters of dispute by holding discussions and coming to an agreement which can be mutually agreed by them. It also refers to coming to closing a business deal or bargaining on some product. This is one of the most important skills a graduate must posses because workplace tends to have disputes, arguments which if not resolved could end up in unpleasant situations.

Oral Communication

This skill helps in expressing information to individuals or groups effectively, taking into account the audience and the nature of the information. A clear and convincing oral presentation evokes good response and has desirable effect on the audience which is a key to managerial effectiveness.

Interpersonal

Interpersonal skills reflect good understanding, courtesy, tact, and concern for others. It helps in developing and maintaining relationships. It helps in dealing with people who are difficult, hostile and distressed. It helps in relating well with people from varied backgrounds and situations. It is also sensitive to individual differences.

Problem solving

Problem solving skills deal with the ability to identify problems and gather relevant information to solve them. It uses sound judgment to generate alternatives and evaluate them to make recommendations, which help in solving the problems.

Decision making

This is an ability to make sound, well informed and objective decisions. It also perceives the impact and implications of decisions, leads to commitment even during uncertain situations to accomplish organizational goals.

Self management

It sets well-defined and realistic personal goals, displays high level of initiative, effort and commitment towards completing assignments in a timely manner. It helps to demonstrate responsible behaviour, ability to work under minimal supervision, and motivation to achieve.

Effective thinking

Effective thinking is not creative thinking or lateral thinking. It is being aware of and improving ones own thinking. An effective thinker consciously works at making his/her thinking more rational, clear, accurate, and consistent. An effective thinker is one who utilizes a combination of critical and creative thinking within the reasoning process.

Continuous learning

This skill assists in developing the ability to learn new methods and techniques to acquire and apply new knowledge, skills and working methods. This helps one to use different training methods, provide feedback and capitalize on other opportunities for self learning and development.

Mind mapping

Mind mapping helps you break large projects or topics down into manageable chunks, so that you can plan effectively without getting overwhelmed and without forgetting something important. As such, they engage much more of your brain in the process of assimilating and connecting information than conventional notes do.

Written Communication

It recognizes the use of language especially English in one's professional life to transfer ideas, express feelings, report and communicate effectively at the work place.

Presentation

Presentation skills have become the hallmark of successful managers. Effective presentation skills help in influencing the perceiver and reduce problems or doubts that may arise due to lack of clarity about information.

Adaptation to working condition

Once a worker begins to work for a particular organization he may have to work in a different environment due to the requirements of the job. If they are not adaptive to working in different environments they will become unhappy and non productive.

Coping with challenges

A person's work life presents oneself with a number of challenges which are essential for the organizational effectiveness. A profound coping ability is necessary to overcome challenges without being frustrated. This skill is very important to a graduate in a competitive market, where target setting is commonplace.

Attitudinal flexibility

An attitude can be defined as a predisposition or a tendency to respond positively or negatively towards a certain idea, object, person, or situation. Attitude influences an individual's choice of action, and responses to challenges, incentives, and rewards. Since a worker has to encounter all these on a huge range, having a high degree of flexibility of attitudes is necessary for organizational effectiveness.

3 METHODOLOGY

A questionnaire comprising 18 statements was prepared to assess the importance of 18 soft skills types deemed to be relevant for graduate employees working in private sector organizations. All framed statements were close end type. The questionnaire was administered among four categories of stakeholders namely, managers, academics, graduates and current students. The technique of Relative Importance Index (RII) was adopted to determine the relative importance of the selected soft skills. The recipients were expected to put down their responses, to the 18 statements, in terms of ratings ranging from 1, 2, 3, 4, 5 (1 - strongly disagree, 2-disaree, 3 neither agree nor disagree, 4-agree, 5-strongly agree).

The respondents constituted 32 managers (8 top level and 16 middle level) from private sector, 24 graduates (8 OUSL graduates, 9 'the other local graduates' and 7 foreign graduates), 22 academics and 28 current students of OUSL (12 Engineering Technology, 8 Humanities and Social Sciences and 8 Natural Sciences). The RII of each soft skill was computed by adopting the following formulae:

$$RII = \frac{\sum W}{A * N} \quad \ldots.(1)$$

where W is the weighting given to each soft skill by the respondents (ranging from 1 to 5), A is the highest weight (ie. 5 in this case) and N is the total number of respondents.

It was envisaged to select the five most significant soft skills types based on the RII assigned to each soft skill in this survey. Subsequently, a second questionnaire survey was conducted in order to asses the current level of competence of the five selected soft skills among the following categories; OUSL graduates (8), 'the other local graduates' (9) and foreign graduates (7). The perceptions of the respondents were measured in the same way as in the first survey. In keeping with the objectives of the study the respondents were requested to indicate their perception using their working experience with the graduates. This survey was conducted among the top and middle level managers of the renowned private sector establishments in both industrial and service sectors. A total of thirty two managers responded by rating the responses on a Likert type scale of 1-5. In a similar manner to RII, a Relative Competence Index (RCI) was computed by adopting the following formulae:

$$RCI = \frac{\sum W}{A * N} \quad \ldots.(2)$$

A brain storming session was conducted with the participation of four middle level managers and three academics who are experts on training in soft skills. The questions asked at the brain storming session were focused on identifying the soft skills significant for graduates and the following soft skill types were short listed:

- Leadership
- Time management
- Stress management
- Team work
- Negotiation
- Oral Communication
- Interpersonal
- Problem solving
- Decision making
- Self management
- Effective thinking
- Self learning
- Mind mapping
- Written Communication
- Presentation
- Adaptation to working condition
- Coping with challenges
- Attitudinal flexibility

4 RESULTS AND DISCUSSION

The RII for each soft skill type was computed with respect to the four categories of stakeholders namely, employers, academics, graduates and current students. RIIs, mean RII and ranking for each soft skill type are depicted in Table 1. The mean RII of each skill type is graphically presented in Figure 1.
When mean RII was computed, no weighting was assigned to any particular category of stakeholders since no basis could be figured out for such a weighting. Five soft skills carried fairly high RIIs namely Interpersonal (0.869), Leadership (0.864), Oral Communication (0.862), Decision making (0.850) and Teamwork (0.850); the mean weightings are given in parentheses.

Interpersonal
Lately, the working environment is increasingly becoming interactive, and the hierarchical structure is fading away. A good understanding among workers is expected of in discharging duties in order to keep a pleasant working environment. Workers at various levels have to be courteous and tactful in getting work done, which is mainly done by way of requesting rather than ordering, a practice being discouraged in the office environment. Although superior-subordinate work environment is still continuing to fulfill the requirement of inevitable formal functioning of the office (for various approvals) superiors are supposed to show respect, empathy and concern to subordinates.

Table 1 - Relative Importance Index (RII) of soft skills

Soft Skill Type	Relative Importance Index (RII)				Mean RII	Ranking
	Employers	Academics	Graduate	Current Students		
Leadership	0.916	0.890	0.890	0.758	0.864	2
Time management	0.800	0.850	0.850	0.714	0.804	10
Stress management	0.756	0.830	0.830	0.772	0.797	11
Team work	0.898	0.850	0.850	0.800	0.850	5
Negotiation	0.700	0.640	0.640	0.630	0.653	18
Oral Communication	0.850	0.900	0.900	0.796	0.862	3
Interpersonal	0.904	0.900	0.900	0.772	0.869	1
Problem solving	0.770	0.850	0.850	0.754	0.806	9
Decision making	0.800	0.900	0.900	0.800	0.850	4
Self management	0.800	0.910	0.910	0.766	0.847	8
Effective thinking	0.770	0.700	0.700	0.742	0.728	16
Continuous learning	0.800	0.900	0.900	0.788	0.847	7
Mind / concept mapping	0.746	0.700	0.700	0.708	0.714	17
Written Communication	0.762	0.832	0.832	0.734	0.790	12
Presentation	0.784	0.800	0.800	0.724	0.777	15
Adaptation to working condition	0.900	0.850	0.850	0.794	0.849	6
Coping with challenges	0.898	0.748	0.748	0.724	0.780	14
Attitudinal flexibility	0.900	0.750	0.750	0.758	0.790	13

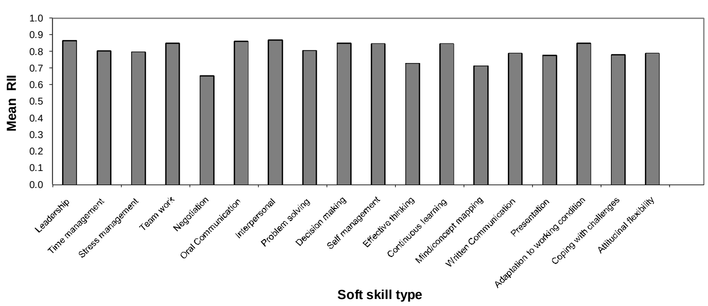

Figure 1- **Relative Importance Index (RII) of soft skills**

These are the reasons why the stakeholders perceive interpersonal skills to be the most important type of soft skill that graduates seeking employment should possess.

Also the competence in this skill is required to deal with workers who are non cooperative, difficult, hostile and distressed. Since people from varying cultures, background, age group can join the workplace one has to be sensitive to individual differences.

Leadership

The new trend is to get the work done by giving tasks or assignments to workers. One has to be adept at leadership which is the factor that influences, motivates and challenges the members to achieve the predetermined goals. In modern working environment imposition of rules and regulations is not encouraged and so skills in leadership are of very high importance to accomplish the given tasks. The stakeholders perceive this as an important skill because market is becoming competitive and success of ventures to a greater extent depends how much one can outperform the competitor. This can only be achieved through a potent team led by a good leader.

Oral Communication

A worker is expected to express ideas and convey information to individuals, and groups effectively. Success of a business depends on how well you can convince the prospective customers. The stakeholders know the power of clear and persuasive oral presentations in evoking favourable response from the audience which is a key to outperform the competitors and to launch new product and services.

Decision making

Irrespective of the position in the organization any worker has to make decisions in discharging duties. To ensure that the decisions made are profound, one must develop an ability to make informed, timely and objective decisions. Ideally, this skill enables the worker to make decisions that lead to commitment even during uncertain situations to accomplish organizational goals. Decision making is considered an important skill by stakeholders, lack of which makes them indecisive and seek decisions of the superior constantly.

Teamwork

When job tasks are analysed in the present context, one will realize that they are mostly teamwork. Firms have begun to realize that team work encourages members and facilitates cooperation among members. It also instills a sense of pride, trust and group identity which will make them do more than their individual job tasks. This will help the work to progress smoothly with minimum interruptions. Since the stakeholders are conscious about the productivity, this is rated as an important skill.

In the second survey, the employers' perception on the competence of these five skills was assessed. Table 2 depicts the Relative Competence Index (RCI) of the five most important soft skills among the three categories of graduates namely, OUSL graduates, 'other local graduates' and foreign graduates. Figure 2 provides a graphical representation of RCI of the five soft skills among the three categories of graduates.

Table 2 - Relative Competence Index (RCI) of soft skills

Soft Skill Type	OUSL Graduates	Other local Graduates	Foreign Graduates
Interpersonal	0.724	0.742	0.842
Leadership	0.710	0.728	0.782
Oral Communication	0.684	0.742	0.854
Teamwork	0.666	0.714	0.882
Decision making	0.728	0.800	0.782

In comparison to both 'other local' graduates and foreign graduates, the OUSL graduates perform poorly in all important soft skills namely Interpersonal, Leadership Oral communication, Teamwork and Decision making. However, Oral communication and teamwork skills of the OUSL graduates are far off from 'other local' and foreign graduates. The fact that OUSL graduates underperform significatly with respect to the above two skills can be attributed to the deficiency in the mode of imparting knowledge, i.e. Open Distance Learning (ODL). Since OUSL students do not attend lectures akin to conventional universities the number of face to face interactive sessions with the academics is fewer. These kinds of skills can only be acquired through participating in interactive sessions with academics, instructors and fellow students. This leaves OUSL students having less opportunity to master both these skills of Oral communication and Teamwork.

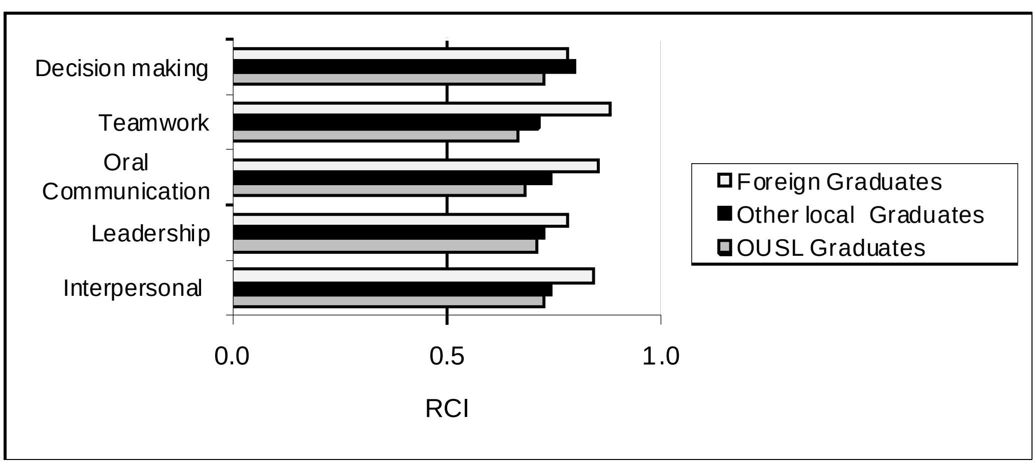

Figure 2 - Relative Competence Index (RCI) of soft skills

According to the analyses and the literature findings, the possible causes for the problems can be summarized as below:

- Failing to identify the emerging needs and expectations of stakeholders concerning soft skills
- Not having a systematic plan to incorporate useful soft skills components into academic programmes
- Greater attention is being paid to the development of hard skills but scant attention to developing soft skills of undergraduates.
- Neither a compulsory nor elective course is offered to train and impart knowledge in soft skills

The above analysis shows OUSL graduates are lacking in all the five most important soft skills. This indicates that OUSL programmes are not adequately geared to improve the essential soft skills which the potential employers are looking for. It is obvious that lack of proficiency in these important soft skills affects the employability of fresh graduates as well as the career progression of those who are already employed. The forming of the Career Guidance Unit (CGU) in year 2009 at the OUSL is an important step towards improving the employability of undergraduates. The CGU is currently engaged in conducting soft skill programmes for the students registered at the OUSL.

5 CONCLUSION

The literature review identified 32 types of soft skills in which graduates should be competent with in order to enhance employability. Through a brain storming session, participated by four types of stakeholders namely, employers, academics, graduates and current students, this list was reduced to a manageable 18 soft skills, which are essentially needed by the graduates seeking employment in the industry.

According to the perceptions of the four types of stakeholders, the soft skills were ranked, based on RIIs, in the following manner (the rank is given in parentheses).

Interpersonal (1), Leadership (2), Oral Communication (3), Decision making (4), Team work (5), Adaptation to working condition (6), Continuous learning (7), Self management (8), Problem solving (9), Time management (10), Stress management (11), Written Communication (12), Attitudinal flexibility (13), Coping with challenges (14), Presentation (15), Effective thinking (16), Mind mapping (17), Negotiation (18).

In order to assess soft skills competence among graduates based on the type of degree awarded, the five most important skills were adopted, namely Interpersonal (1), Leadership (2), Oral Communication (3), Decision making (4), Team work (5). Using the Relative Competence Index (RCI) the soft skills competence of the OUSL, 'other local' and foreign graduates were computed.

In general, competence of soft skills of foreign graduates is far greater than that of OUSL graduates and 'other local' graduates. However, soft skills competence of 'other local' graduates is only marginally better than OUSL graduates. According to RCI, with respect to all the five types of soft skills , the OUSL graduates perform poorly in relation to both 'other local' and foreign graduates. Further, Oral communication and Teamwork skills of the OUSL graduates are far lower than those of 'other local' and foreign graduates. The opportunities available for the OUSL graduates to improve these skills are limited due to the mode Open Distance Learning (ODL) in which they pursue their programmes. Hence, the courses should be conducted in such a way that they contain an optimum number of activities directly geared to improve Oral communication and Teamwork skills.

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Design of a Flight Control System in Compliance with Fling and Handling Quality Requirements

M. Ruwan Thilina Perera

Department of Mechanical Engineering, The Open University of Sri Lanka, Nawala, Nugegoda, Sri Lanka.

Email: ruwan.aero@gmail.com Tele: +94112881477

Abstract- *This paper presents the design of a flight control system (FCS) that offers the Aerosonde Unmanned Vehicle (UAV) with stability and control characteristics and capabilities of a classical aerial piloted aircraft.*

The design problem was formulated with a narrow focus on the following aspects of the UAV.

- *The un-augmented open loop 6-DOF Aerosonde exhibits poor stability and control characteristics in compliance with MIL-F8785C flying quality standards.*
- *As in most classical fixed wing aircrafts, the control inputs to Aerosonde result in pitch, roll and yaw rate responses (rate command characteristics). This has made manual trimming of the UAV, at a given flight condition, with a human pilot-operator closing the loop, a daunting task.*

In the first phase of the design, a stability augmentation system was developed to improve the stability and control characteristics of the UAV compliance with MIL-F8785C flying qualities standard. In the second phase, a Rate-Command-Attitude-Hold system has been implemented to the FCS for longitudinal control of the UAV. In the third phase, an Auto-Stabilizer was deigned to control the Lateral-Directional command-response characteristics of the UAV.

Both the Longitudinal and Lateral-Directional FCSs have been tested and simulated using linear and non-linear flight dynamic models of the UAV.

Keywords: *UAV, Flight Control, Stability and Control, Flying Qualities*

Nomenclature

A – State matrix
p – Roll rate (deg/s)
r – Yaw rate (deg/s)
v – Lateral velocity (m/s)
h – Altitude (m)
x – State vector
K_w – Normal velocity gain constant
K_q – Axial velocity gain constant
K_r – Yaw rate gain constant
K_{ari} – Aileron-rudder interlink gain
q_d – Pitch rate demand (deg/s)
T_w – Washout filter time constant (s)
Greek Letters

B – Input matrix
q – Pitch rate (deg/s)
u – Axial velocity (m/s), Input vector
w – Normal velocity (m/s)
y – Output vector
K_u – Axial velocity gain constant
K_θ – Pitch angle gain constant
$K_{\varepsilon q}$ – Pitch rate integral gain const
K_p – Roll rate gain constant
K – Gain vector
J – Performance index

ϕ – Roll angle (deg)
θ – Pitch angle (deg)
ψ – Yaw angle (deg)
η – Elevator angle (deg)
ζ – Rudder angle (deg)
ξ – Aileron angle (deg)
τ – Engine throttle position
β – Sideslip angle (deg)
ζ_s – Short period pitch oscillation damping ratio
ζ_p – Phugoid damping ratio
ζ_{dr} – Dutch roll damping ratio
ω_p– Phugoid natural frequency (rad / s)
ω_{dr} – Dutch roll natural frequency (rad / s)
T_r – Roll subsidence time constant
ε_q – Integral of pitch rate error
ω_s – Short period natural frequency (rad / s)
ω_w– Washout filter break frequency (rad / s)

1 INTRODUCTION

UAVs have become a great source for future aerial operations. However, in Sri Lanka, UAV technology has been in a slow growth. The research work carried out by Tenakoon and Munasinghe (2008) to develop a UAV controller system provides a UAV good manoeuvrability with minimum overshoot settling time without oscillation. However, it would not guarantee flying and handling quality requirements of a UAV. Flying and handling quality requirements are of high importance, if the UAV is to be controlled by a human operator.

The proposed UAV for this research is Aerosonde which has been built by Aerosonde Ltd. It is a small UAV designed to collect weather data over oceans and remote areas. The aerodynamic design of the UAV is largely classical and therefore building a similar model for further research work only needs a reasonable and a manageable effort.

1.1 Aim

In general, UAVs are controlled autonomously or from a ground station human controller. In either event, a suitable flight control system should be implemented on the UAV to achieve objective tasks and missions.

Due to poor dynamic properties of the natural Aerosonde airframe (in compliance with MIL-F-8785C flying quality standards), it is purely impossible for a human operator to control the open loop UAV. Therefore, the aim of this ***flight control system*** (FCS) design is to make it possible for a human operator to control the UAV. A classical flight dynamics principle defines the properties of FCSs that a piloted aircraft should have. This FCS design incorporates those properties and therefore it enables the UAV to attain control characteristics of a classical piloted aircraft.

In addition, the design can later be extended to implement robust, optimal and trajectory planning control algorithms.

1.2 Aerosonde Dynamics

For this research, the full non-linear Aerosonde dynamic model available on Aerosim Matlab / Simulink block set has been used.

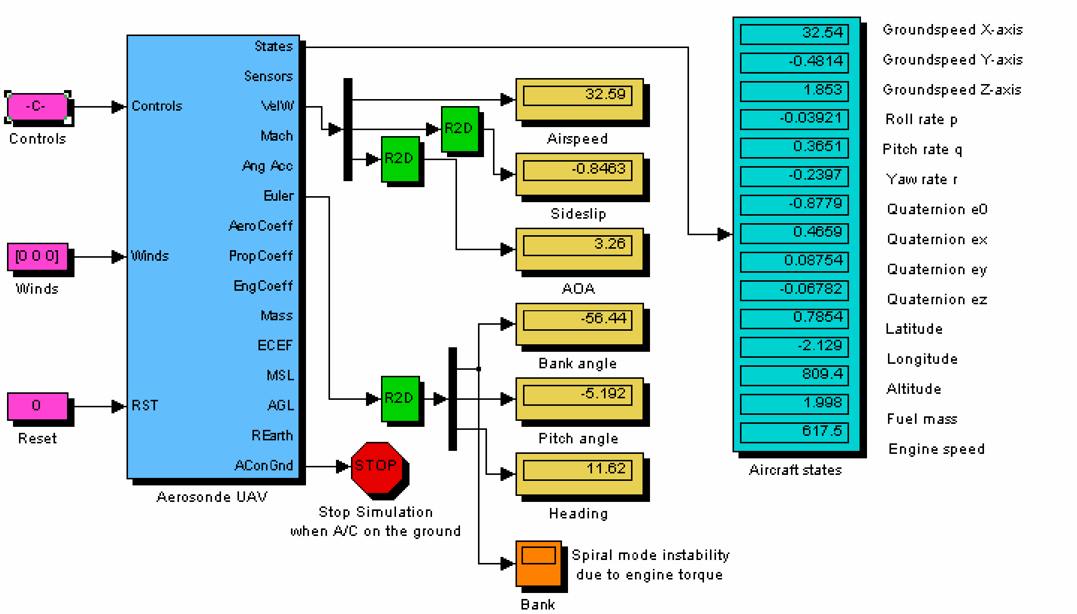

Figure 1 - Nonlinear Aerosonde open loop model

The control inputs to the UAV are deflections of Flap, Elevator, Aileron & Rudder control surfaces and change in Engine throttle position. In addition, the above model allows controlling of fuel mixture and ignition inputs and however, they are set at 13 and 1 for all operations of this research.

1.2.1 Trimming and Linearization

Before applying any flight control algorithm the nonlinear model (Aerosim Aerosonde model) should be trimmed (steady-state equilibrium) and linearized.

Trimming

By definition, steady-state wings level flight and steady turning flight conditions are permitted to be trimmed flight conditions. If the change in atmospheric density with altitude is negligible, a wings-level climb and a climbing turn can also be taken as trimmed flight conditions (Cook, 1997).

To design the objective FCS, the UAV is trimmed at the below mentioned wings-level flight condition with the following constrains applied on the states.

$$\phi,\dot{\phi},\dot{\theta},\dot{\psi} \equiv 0 \quad (\therefore p,\ q,\ r \equiv 0)$$

Flight condition:

Trim airspeed – 30 m / s
Trim altitude – 1000 m
Trim bank angle – 0 rad
Flap setting – 0

The result obtained is:

$$\begin{pmatrix} u_e = 29.99 m/s \\ v_e = 0.01 m/s \\ w_e = 0.74 m/s \\ p_e = 0 \deg/s \\ q_e = 0 \deg/s \\ r_e = 0 \deg/s \\ \phi_e = -0.02 \deg \\ \theta_e = 1.41 \deg \\ \psi_e = -0.44 \deg \\ h_e = 1000 m \end{pmatrix}, \ u_{trim} = \begin{pmatrix} \eta_e = 2.02 \deg \\ \xi_e = 0.46 \deg \\ \zeta_e = 0.05 \deg \\ \tau_e = 1.1054 \end{pmatrix}, \ y_{trim} = \begin{pmatrix} V_e = 30 m/s \\ \beta_e = 0.02 \deg \\ \alpha_e = 1.41 \deg \\ \phi_e = -0.02 \deg \\ \theta_e = 1.41 \deg \\ \psi_e = 359.56 \deg \\ h_e = 1000 m \end{pmatrix} \quad (1.1)$$

The trim state can be validated by simulating the model for few seconds with $u = u_{trim}$ and $x_0 = x_{trim}$.

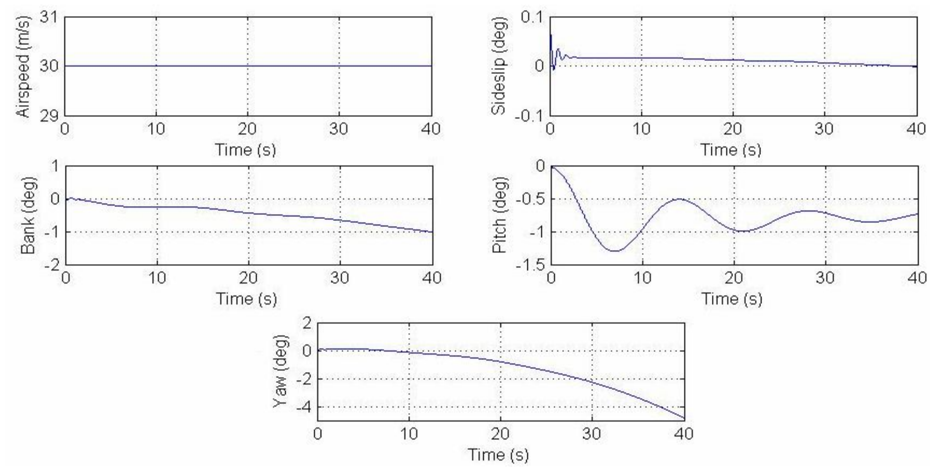

Figure 2 - Nonlinear Aerosonde in trim

<u>Linearizing</u>
The next objective is to obtain a linear approximation of the non-linear trimmed UAV model. Linear approximations are much more desirable to work with as it is easier to predict the behaviour.

The Matlab *linmod* function is used to linearize the model numerically and this brings us to a state-space representation of the form:

$$\dot{x} = Ax + Bu \quad (1.2)$$

Where: $x = [u \ w \ q \ \theta \ v \ p \ r \ \phi]^T$

Thereafter, the state-space model is decoupled into longitudinal and lateral / directional senses by assuming that the coupling factors are insignificant. After decoupling the state equation, two state-space linear representations are obtained for Longitudinal and lateral-directional dynamics.

Where: Longitudinal states $x = [u \ w \ q \ \theta]^T$
Lateral-Directional states $x = [v \ p \ r \ \phi]^T$

1.2.2 Stability

Two and three dynamic stability modes are described respectively in the longitudinal and lateral-directional senses.
Longitudinal modes: *Short period pitch oscillation and Phugoid mode*
Lateral-Directional modes: *Roll subsidence mode, Spiral mode and Dutch roll mode*

Before deciding the flight control law parameters,
Stability properties of the above modes of the UAV must be checked. Since command-response characteristics of the UAV are expected to be similar to a piloted aircraft, any necessary stability augmentation is done compliance with MIL-F-8785C flying quality standards (Anon, 1980). The American Military Specification MIL-F-8785C specify acceptable stability and control standards, more commonly known as *flying qualities requirements*, that a piloted aircraft should achieve.

1.2.3 Flying Qualities

MIL-F-8785C is defined for a range of aircrafts depending on the *class of the aircraft* and *flight phase* (Cook, 1997; Anon, 1980). Aerosonde is a class 1 aircraft with manoeuvre and mission categories lie in flight phase category C.

The ***Short period pitch oscillation*** damping for the Aerosonde should lie in the following regions. Level 1 flying qualities means a fully functional aircraft with 100% capability of achieving the missions that are described in its flight phase category.

Table 1 - Level 1, 2 and 3 short period pitch oscillation damping

Flight Phase	Level 1		Level 2		Level 3
	$\zeta_{s\,min}$	$\zeta_{s\,max}$	$\zeta_{s\,min}$	$\zeta_{s\,max}$	$\zeta_{s\,min}$
CAT C	0.50	1.30	0.35	2.00	0.25

The *Short period pitch oscillation* natural frequency should lie within the following range.

ω_s: $4.0 <= \omega_s <= 25$ (rad/s)

For the ***phugoid*** mode the flying qualities requirements can be summarized as follows.

$\omega_s/\omega_p > 0.1$

ζ_p:- $0.04 <= \zeta_p$

Dutch roll, ***Roll subsidence*** and ***Spiral*** mode level 1 stability requirements are shown below;

Table 2 - Level 1 lateral-directional flying qualities

Mode	Level 1 Requirements
Dutch roll mode	$\zeta_{dr} \geq 0.19$, $\omega_{dr} \geq 1.0$ rad/s, $\omega_{dr}\zeta_{dr} \geq 0.35$ rad/s
Roll subsidence mode	$0 \geq T_r \geq 1.0$ s
Spiral mode	When unstable: $t_{2\phi} \geq 12$ s

It is significant that more emphasis has been placed on the short period stability modes (short period pitch oscillation and Dutch roll) when defining flying qualities requirements.

1.3 Flight Control System Design Techniques

To design aircraft control systems, both classical and modern control techniques are used. The general norm of classical design is loop closure to provide inner-rate feedback around the plant for the purpose of artificial damping improvement. In conjunction with this, standard integral compensator structures are used to eliminate steady state errors. Modern control techniques on aircraft FCSs have been employed since mid 80's (Stevens and Lewis, 1992). However, modern techniques are not highly encouraged on aircraft control due to their dependency on selecting large number of parameters such as *performance index weighting matrices*.

There are many classical Command and Stability Augmentation Systems developed for aircraft control such as *Longitudinal Rate Command Attitude Hold (RCAH)* controller, C* controller (Example: A320), C*-U controller and *Lateral-Directional Auto-stabilizer* (LDA) controller etc.

1.3.1 Longitudinal Flight Control System Design

The RCAH controller has been used for longitudinal control of the Aerosonde as the dynamic structure of the aircraft and its stability and control characteristics should remain classical. One reason for this is that classical control and stability characteristics can easily be tuned in compliance with the Flying Quality standards. In addition, when controlling the UAV on the Simulation or Real-Time the human intuition appreciates classical command-response characteristics. This RCAH design has been successfully used on F-16 fighter jet.

1.3.2 Lateral-Directional Flight Control System Design

The LDA controller is proposed to use for lateral and directional control of the UAV with the same reasoning as mentioned above. Since the trim state is assumed in both lateral and directional senses, the LDA design is mainly concerned with manoeuvring the UAV about the trim state.

2 LONGITUDINAL FLIGHT CONTROL SYSTEM DESIGN

As mentioned in the introduction, the linearized longitudinal state-space representation of the trim state can be shown as below (For elevator inputs only).

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.2690 & 0.4017 & -0.7248 & -9.7973 \\ -0.5318 & -4.9550 & 29.3296 & -0.2404 \\ 0.3421 & -5.2290 & -5.7174 & 0 \\ 0 & 0 & 1.0000 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} -0.2976 \\ -3.4212 \\ -46.308 \\ 0 \end{bmatrix} \eta \tag{2.1}$$

2.1 Flying qualities requirements

With reference to MIL-F-8785C, the longitudinal flying qualities are analysed.

Table 3 - Open loop level 1 longitudinal flying qualities

Mode	Level 1 Requirements	Aerosonde
Short Period Pitch Oscillation	$0.5 \geq \zeta_s \geq 1.30$ $4.0 <= \omega_s <= 25$ (rad / s)	$\zeta_s = 0.396$ $\omega_s = 13.5$ rad / s
Phugoid mode	$\omega_s / \omega_p > 0.1$ $0.04 <= \zeta_p$	$\omega_s / \omega_p = 27.6$ $\zeta_p = 0.274$

It is clear that the short period damping is too low while the mode frequency meets the requirements. The phugoid mode flying qualities requirements are already well within the range. Therefore the feedback gains should ensure the improvement in short period mode damping.

2.2 Pitch Rate Command-Attitude Hold Command and Stability Augmentation System (CSAS)

In order to design the objective CSAS design, a pitch rate feedback proportional gain K_q plus integral (P+I) controller is incorporated on pitch rate feedback to elevator. Since the state-space representation is a multivariable control problem, all the other proportional state feedback gains [K_u, K_w, K_θ] should also be included into the design. Proportional gains are used to provide the system with desired closed loop stability and rate command characteristics while the integral gain, $K_{\varepsilon q}$ drives the rate command error signal to zero.

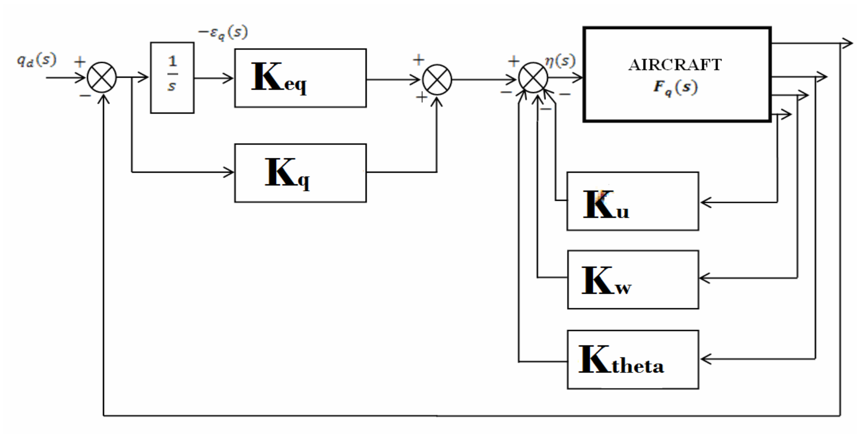

Figure 3 - RCAH system structure

Therefore the design objective is to find appropriate values for the proportional and integral gains with the following constrains applied.

The augmented UAV should meet MIL-F-8785C and the short period dynamics should be *second order like*. Therefore any additional dynamics introduced by the integrator should not be visible to the human controller.

2.2.1 Augmenting the Open Loop State Equation

In order to find appropriate values for the proportional and integral gains it is necessary to have the integral state variable available as an additional state.

Extra state variable: $\varepsilon_q(t) = \int (q(t) - q_d(t))dt$ (2.2)

Where, the state equation may be written: $\dot{\varepsilon}_q(t) = (q(t) - q_d(t))$ (2.3)

Now the integral state equation can be augmented into the original longitudinal state equation as follows;

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{\varepsilon}_q \end{bmatrix} = \begin{bmatrix} -0.2690 & 0.4017 & -0.7248 & -9.7973 & 0 \\ -0.5318 & -4.9550 & 29.3296 & -0.2404 & 0 \\ 0.3421 & -5.2290 & -5.7174 & 0 & 0 \\ 0 & 0 & 1.0000 & 0 & 0 \\ 0 & 0 & 1.0000 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \\ \varepsilon_q \end{bmatrix} + \begin{bmatrix} -0.2976 \\ -3.4212 \\ -46.308 \\ 0 \\ 0 \end{bmatrix} \eta + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -1 \end{bmatrix} q_d \qquad (2.4)$$

Then the open loop longitudinal state equation may be written as;

$$\dot{x} = Ax + Bu + Nv \qquad (2.5)$$

2.2.2 Designing the closed loop system stability

The feedback control law can be defined as follows;

$$u = -Kx + Mv \qquad (2.6)$$

where K is the feedback gain vector and M is the feed forward gain scalar which is assumed to be 1 at this instance (therefore no feed forward gain is illustrated in Figure 1). By substituting the control law into the previous state representation the closed loop state-space equation is obtained in the general form.

$$\dot{x} = [A - BK]x + [BM + N]v \qquad (2.7)$$

where K= [K_u K_w K_q K_θ $K_{\varepsilon q}$]

Now the task is to select an appropriate feedback gain vector K such that it provides level 1 flying qualities in compliance with MIL-F-8785C and objective command-response characteristics. This has been achieved by solving a Linear Quadratic Regulator (LQR) control problem.

<u>LQR control problem</u>

If the open loop state-space representation is $\dot{x} = Ax + Bu$, the problem is to find an optimal constant feedback controller K_0 such that it minimizes the following quadratic cost function.

$$J = \int_0^\infty (x^T(t)Qx(t) + u^T(t)Ru(t))dt \qquad (2\,.7)$$

where $u(t) = -Kx + Mv$, Q and R are weighting matrices.

LQR Solution:

The Optimal controller is

$$K_o = R^{-1}B^T P \qquad (2.8)$$

where $P = P^T \geq 0$ is the solution of

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \qquad (2.9)$$

Matrix *P* is a positive definite (or semi-definite) matrix where $x^T Px \geq 0$ for all $x \neq 0$.

The choice of Q: As observed previously, it is desired to obtain level 1 flying qualities of the short period mode and pitch rate command-attitude hold characteristics. The short period mode is significant (dominant) in w and q responses while the integral action is critical in command-response characteristics and therefore Q can be selected such that it gives a considerable emphasis on K_w, K_q and $K_{\varepsilon q}$ gains and less emphasis on K_u and K_θ gains. After a series of trials the following Q matrix was selected.

$$Q = diag\left(10\times10^{-10}, 10\times10^{-4}, 10\times10^{-4}, 10\times10^{-10}, 100\right)$$

R is selected to be 1 to correctly scale the control inputs.

After solving the above problem on Matlab the optimal feedback gain vector was found to be;

K= [-0.0092 0.0897 -0.4535 -0.0120 -9.9799]

<u>Closed loop system analysis</u>

The closed loop state equation,

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{\varepsilon}_q \end{bmatrix} = \begin{bmatrix} -0.2718 & 0.4284 & -0.8597 & -9.8009 & -2.9700 \\ -0.5634 & -4.6482 & 27.7783 & -0.2815 & -34.1431 \\ -0.0860 & -1.0763 & -26.7158 & -0.5560 & -462.1459 \\ 0 & 0 & 1.0000 & 0 & 0 \\ 0 & 0 & 1.0000 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \\ \varepsilon_q \end{bmatrix} + \begin{bmatrix} 0.7142 \\ 8.2109 \\ 111.1390 \\ 0 \\ -1.0000 \end{bmatrix} q_d \qquad (2.10)$$

w and q transfer functions:

$$\frac{q(s)}{q_d(s)} = \frac{-46.3079s\,(s-9.98)\,(s+4.511)\,(s+0.3284)}{s\,(s+4.15)\,(s+0.3297)\,(s^2+27.16s+502.5)}$$

$$\frac{w(s)}{q_d(s)} = \frac{-3.4212\,(s+402.7)\,(s-9.98)\,(s^2+0.2756s+0.1813)}{s\,(s+4.15)\,(s+0.3297)\,(s^2+27.16s+502.5)}$$

The closed loop integral lag pole is at (s + 4.15), which equates to a lag time of 0.241 seconds. Thus even if the lag is visible to the pilot it is less intrusive as it is much faster. However, the effect of the integral lag time constant can be diminished by a proper selection of M feed forward gain.

2.2.3 Designing the feed forward gain

Up to now M was taken to be 1, since no information about the integrator pole was available. The feed forward gain determines the *integral zero*. Since the feedback gain vector K is known, the closed loop state equation may now be written as;

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{\varepsilon}_q \end{bmatrix} = \begin{bmatrix} -0.2718 & 0.4284 & -0.8597 & -9.8009 & -2.9700 \\ -0.5634 & -4.6482 & 27.7783 & -0.2815 & -34.1431 \\ -0.0860 & -1.0763 & -26.7158 & -0.5560 & -462.1459 \\ 0 & 0 & 1.0000 & 0 & 0 \\ 0 & 0 & 1.0000 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \\ \varepsilon_q \end{bmatrix} + \begin{bmatrix} 0.7142M \\ 8.2109M \\ 111.139M \\ 0M \\ -1.0000 \end{bmatrix} q_d \qquad (2.13)$$

It can easily be shown that integral zero is given by;

$z = \frac{K_{\varepsilon q}}{M}$, since the integral gain is -9.9799 and integral pole is at 4.15, M = -2.4

w and q transfer functions with the feed forward gain M:

$$\frac{w(s)}{q_d(s)} = \frac{8.2246(s+402.7)(s+4.151)(s^2+0.2756s+0.1813)}{s(s+4.15)(s+0.3297)(s^2+27.16s+502.5)}$$

$$\frac{q(s)}{q_d(s)} = \frac{111.3242s(s+4.511)(s+4.151)(s+0.3284)}{s(s+4.15)(s+0.3297)(s^2+27.16s+502.5)}$$

Inspection of equations indicates that cancellation of the integral pole is exact and therefore the short period mode is *second order like*. The dynamics introduced by the integrator is not visible to the human controller.

The stability characteristics of the closed loop UAV can be shown as follows;

Table 4 - Closed loop level 1 Longitudinal flying qualities

Mode	Closed Loop Aerosonde
Short Period Pitch Oscillation	$\zeta_s = 0.606$ $\omega_s = 22.4$ rad / s
Phugoid mode	$T_1 = 1/0 = \infty$ s $T_2 = 1/0.3297 = 3.03$ s
Integrator lag	$T_{lag} = 1/4.15 = 0.241$ s

It is clear that the closed loop UAV holds level 1 flying qualities with the implemented controller. However, a significant change in the phugoid mode can be seen due to the integral feedback. The significant variable of the phugoid mode is θ and the integral of the pitch rat is also pitch attitude θ. Therefore, due to the change in q feedback integral gain the closed loop phugoid mode has considerably modified. The mode is no longer oscillatory. However, a non-oscillatory phugoid is acceptable with reference to MIL-F-8785C technical literature (Anon, 1980).

2.2.4 Implementing the controller design

The corresponding system structure can be realized as follows,

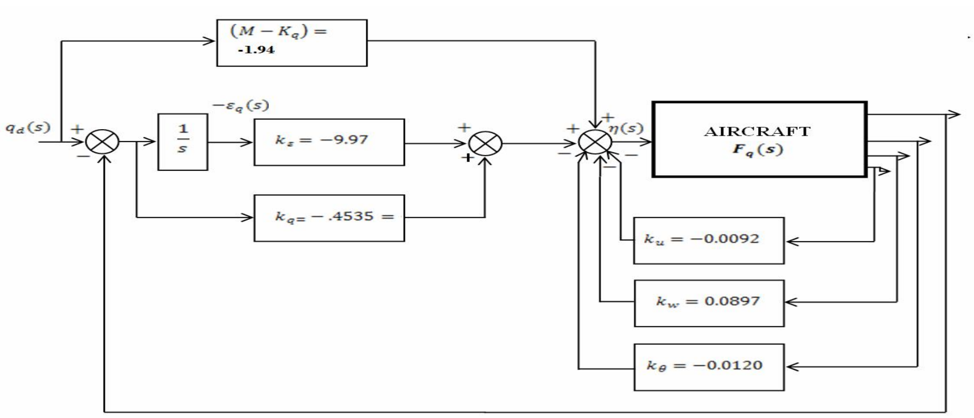

Figure 4 - Equivalent classical P+I controller

Response time histories

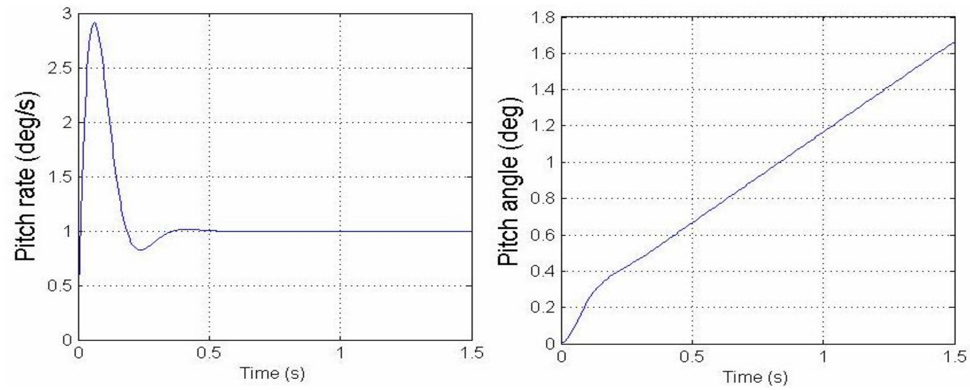

Figure 5 - Closed loop response to a 1^0 pitch rate demand

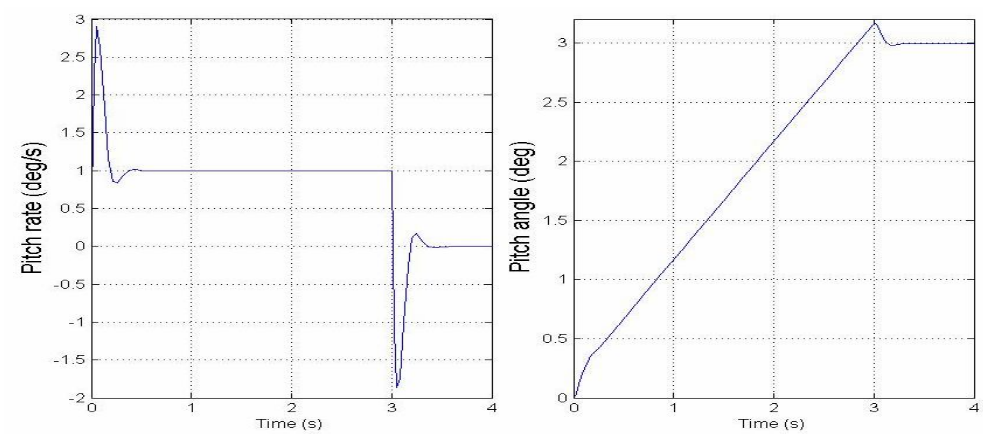

Figure 6 - Closed loop response to a 1^0 pitch rate demand of 3 second

It is clear that the design objectives have been met successfully. The pitch rate responses like a well damped classical aircraft. When a demand for a pitch rate of 1^0/s is held for 3 seconds, the pitch attitude ramps up at 1^0/s and when the input is removed the attitude settles to 3^0 (Figure 6). This precisely describes the rate command-attitude hold characteristics of the design.

3 LATERAL-DIRECTIONAL FLIGHT CONTROL SYSTEM DESIGN

The linearized lateral-directional state-space representation of the trim state for aileron and rudder inputs is shown below;

$$\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -0.7655 & 0.7358 & -29.9906 & 9.7973 & 0 \\ -5.0538 & -24.8886 & 11.9786 & 0 & 0 \\ 0.8202 & -3.2283 & -1.2520 & 0 & 0 \\ 0 & 1.0000 & 0.0245 & 0 & 0 \\ 0 & 0 & 1.0003 & 0 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ p \\ r \\ \phi \\ \psi \end{bmatrix} + \begin{bmatrix} -1.9687 & 5.0251 \\ -172.8548 & 3.1102 \\ -6.8154 & -31.7508 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \xi \\ \varsigma \end{bmatrix} \quad (3.1)$$

Flying qualities requirements

The MIL-F-8785C flying qualities requirements and Aerosonde lateral-directional mode stabilities are summarized as below;

Table 5 - Open loop level 1 lateral-directional flying qualities

Mode	Level 1 Requirements	Aerosonde
Dutch roll mode	$\zeta_{dr} \geq 0.19$ $\omega_{dr} \geq 1.0$ rad/s $\omega_{dr}\zeta_{dr} \geq 0.35$ rad/s	$\zeta_{dr} = 0.146$ $\omega_{dr} = 7.97$ rad/s $\omega_{dr}\zeta_{dr} = 1.16$ rad/s
Roll subsidence mode	$0 \geq T_r \geq 1.0$ sec	$T_r = 0.24$ s
Spiral mode	When unstable: $t_{2\phi} \geq 12$ s	Stable

The Aerosonde meets level 1 requirement with the exception of the Dutch roll mode where the damping is too low.

3.1 Lateral-Directional Auto-Stabilizer (LDA) Design

To manoeuvre the UAV about the lateral-directional trim state with improved turn coordination a typical lateral-directional auto stabilizer is designed (Cook, 1997).

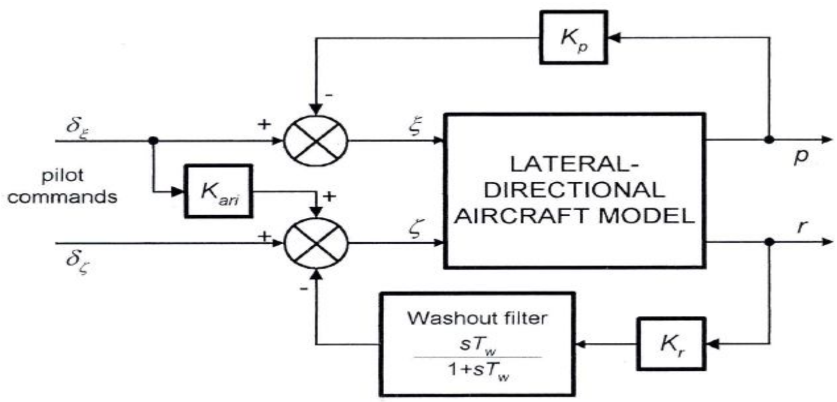

Figure 7 - Lateral-directional auto stabilizer

The LDA design consists of a *roll damper* loop and a *yaw damper* loop. The roll rate feedback gain K_p is used to augment the roll subsidence mode time constant to bring it to an acceptable level. The yaw rate feedback gain K_r is chosen to modify the Dutch roll mode damping ratio. Aileron-rudder interlinks gain K_{ari} is designed to improve roll-yaw coordination in a turn.

During a steady turning flight (with Aileron inputs only), the yaw rate feedback loop would oppose the turn. Therefore, the washout filter is used to prevent this happening by choosing a proper filter time constant T_w.

3.1.1 Design of the Roll Damper

The lateral roll stability of the UAV appears to be adequate and therefore no roll rate feedback to aileron is required ($K_p = 0$).

3.1.2 Design of the Yaw Damper

The loop feedback gain K_r is selected using the yaw rate response to rudder input root locus.

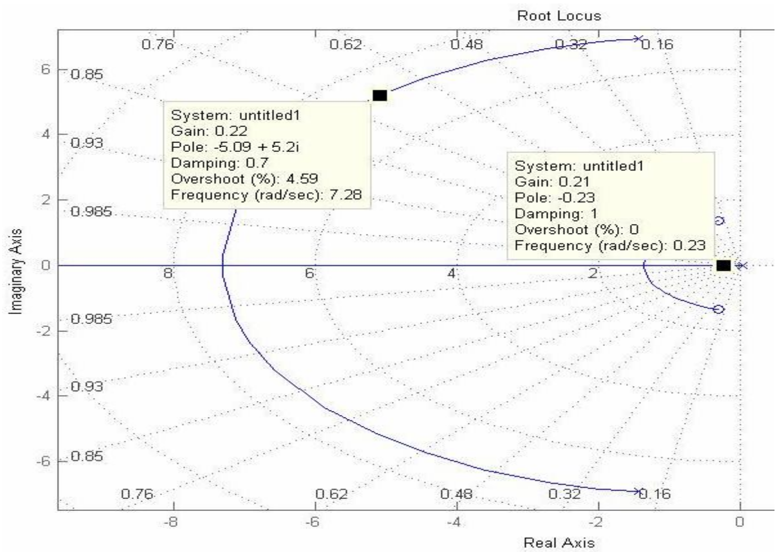

Figure 8 - Root locus plot for yaw rate feedback to rudder

By observing the root locus, it is decided to select a gain of 0.22 for K_r which provides an adequate Dutch roll damping of 0.7. It is also observed that modifications made to the roll and spiral modes due to K_r are minor.

3.1.3 Design of the Washout Filter

The filter is designed in such a way that it attenuates the steady state feedback signal r at low frequencies. However, the feedback signal r should be passed with minimum phase shift and therefore the break frequency ($\omega_w = 1/T_w$) is chosen to be little lower than the Dutch roll frequency. For many piloted aircraft, a filter time constant T_w in between 0.5 and 1 seconds would be satisfactory (Cook, 1997). For the Aerosonde the time constant was chosen to be 0.7s which gives a break frequency of 1.42 rad / s.

3.1.4 Design of the Aileron-Rudder Interlink Gain

The design of the gain K_{ari} is concerned with selecting a value that minimizes sideslip during an aileron command turn. When K_{ari} is selected correctly it will minimize the adverse yaw transient during turn and reduce sideslip to zero. Design of K_{ari} is well described in Stevens and Lewis (1992) where it suggests scheduling K_{ari} as a function of dynamic pressure. However, for the chosen trim flight condition a value of 0.2 is suggested after a series of careful trials.

Response time histories

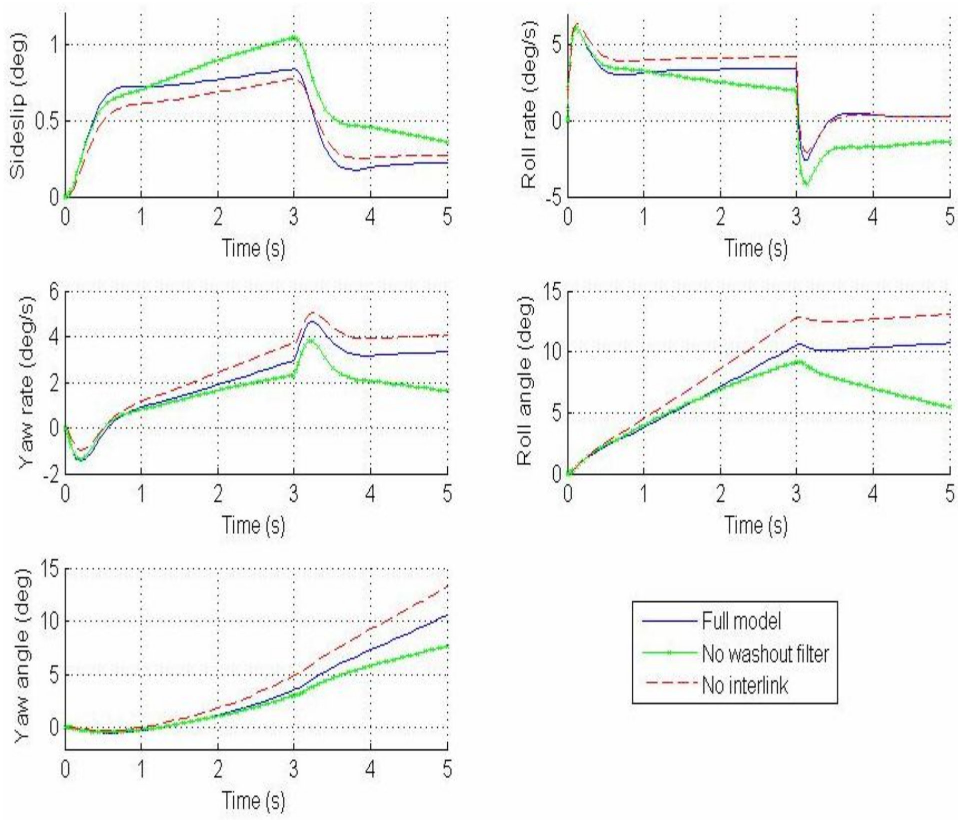

Figure 9 - Response to 1 deg-3s aileron pulse

The turning performance of the aircraft with and without the washout filter and interlink has been compared in the above figure. With the filter, a much steadier yaw rate can be viewed with lesser tendency to roll out. The implementation of the aileron-rudder interlink gain K_{ari} has minimised the sideslip as expected.

It is also observed that manoeuvre capabilities of the UAV about the trim flight condition are adequate. According to above figure, when the aileron input is released, the UAV attains a steady yaw rate with a constant roll angle and a minimum sideslip.

4 IMPLEMENTATION ON THE NONLINEAR MODEL

Finally both the longitudinal and lateral-directional FCSs have been implemented on the non-linear Aerosonde Simulink model.

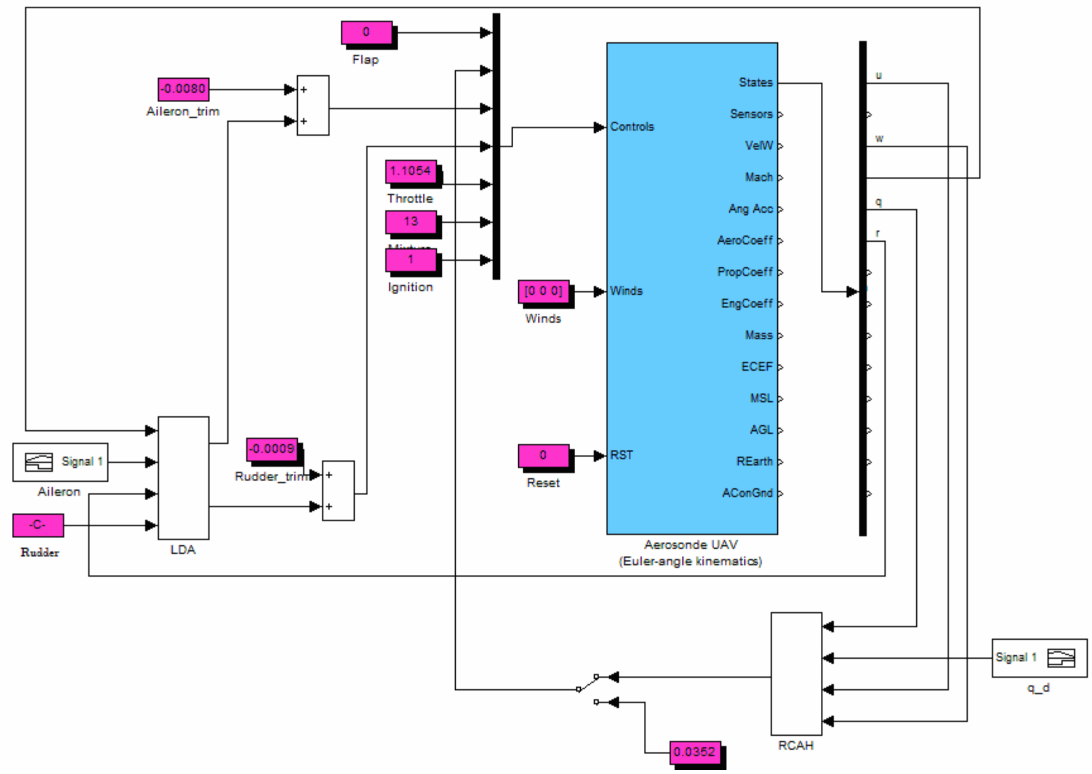

Figure 10 - Nonlinear Aerosonde with RCAH and LDA control loops

4.1 Non-linear Response Time histories

Following are response time histories for a 1.41 deg/s pitch rate demand for 1.8 seconds, .45 deg aileron pulse input for 3 seconds and a continues zero rudder input.

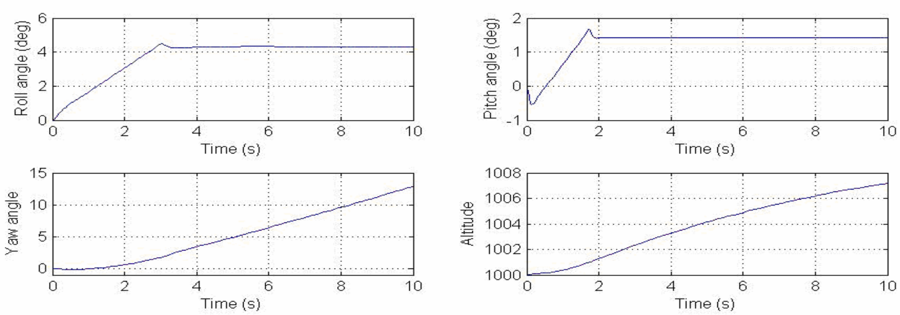

Figure 11 - Modified nonlinear Aerosonde responses

The time histories represent closely related responses to the linear response time histories. However, nonlinear effects are not completely negligible. As illustrated in the linear model, the pitch angle has settled at 1.4 after 1.8 seconds of pitch rate demand and after holding the aileron command for 3 seconds, the roll angle has settled at 4.1 deg as well. However, the altitude keeps increasing with the absence of any altitude holding characteristics of the model.

5 CONCLUSIONS

The full nonlinear Aerosonde model has been trimmed and linearized in order to apply the objective control schemes in compliance with MIL-F-8785C flying qualities requirements to enable the UAV to be controlled by a human operator. Two control schemes were developed in the longitudinal and lateral-directional senses on the linearized model and later the designs were tested on the nonlinear model. The control techniques used for the design are classical theories with the exception of LQR techniques. The FCSs has been proved, to work properly on nonlinear simulation, and to provide command-response characteristics that of a classical piloted aircraft.

However, the design doesn't contain speed and altitude auto-control loops and therefore a constant controlling of the engine throttle is required to maintain the airspeed and altitude. In addition, the FCS parameters have been decided for the chosen trim flight condition. Hence for the design to work over a larger flight envelop, the FCS parameters should be scheduled for changing flight conditions (gain scheduling).

Further this design can be extended to have robust, optimal and path planning control algorithms.

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Calicut Tile Waste as an Alternative Coarse Aggregate for Lower Grade Concretes

B. R. K. C. Dembatapitiya[2], W. D. S. H. Dissanayake[3], T. M. Pallewatta[1*]

[2]Engineer Construction, RSC - Sabaragamuwa, National Water Supply & Drainage Board.
[3]FCivil Engineer, Bauer Equipment South Asia (Pvt.) Ltd.
[1]Professor, Department of Civil Engineering, The Open University of Sri Lanka.

*Corresponding Author: email: tmpal@ou.ac.lk, Tele: +94112881248

Abstract – *The possibility of utilizing waste Calicut tiles as coarse aggregates for concretes was experimentally investigated. Calicut Tile Aggregate (CTA) produced by manual fragmentation of broken tiles, applied to volume batched nominal concrete mixes resulted in expected strength compliance only for a higher strength mix where cement/sand paste fraction was high as compared to coarse aggregate. Modified Standard mixes based on guidelines of ICTAD & BS, ST4 and ST5 were successful in fulfilling workability and one step downgraded strength grade requirements. It was established through this study that CTA is a viable substitute to rock based coarse aggregates for lower grade mass concrete, further substantiated by a cost analysis.*

Keywords*: Concrete, Alternative Materials, Standard Concrete Mixes*

Nomenclature

ICTAD -	Institute for Construction Training & Development	*CTA* -	Calicut Tile Aggregate
		BS -	British Standard

1 INTRODUCTION

Recent development boom in Sri Lanka is mainly manifested in the implementation of infrastructure projects. As a result, construction projects are being executed at a very rapid rate. In a country such as Sri Lanka, apart from funding the major factor affecting construction operations is the availability of construction materials. Concrete being the major material for construction, the availability of concrete at locations in required Grades is a primary consideration for economical and practical operations.

For production of concrete, its primary ingredients in the form of granular bulk (aggregates) and binder (cement) are needed according to stipulated specifications to achieve required workability and stability in the fresh state and strength coupled with durability in the hardened state. Since in concrete, also known as 'Artificial Rock', almost all the solid bulk is aggregate, availability of suitable material for such would be the primary factor governing production. Traditionally, the aggregate subdivided in to coarse and fine gradations is derived from natural rock in the form of crushed rock and sand. Since these natural materials are gradually being depleted from the earth crust without replenishment, scarcity and implications on the environment are inevitable repercussions of long term and wide scale usage. Owing to the fact that even at present, we are faced with both problems mentioned above , alternative solutions should be expediently found.

Fundamentally, the solution could be in the form of either finding of alternative materials or recycling. If waste or demolished concrete could be utilized for new concrete production, it could be considered as recycling, while different materials or the by-products/waste of other production processes could be considered as alternative materials.

Being a hot and humid tropical country, Sri Lankan buildings were traditionally topped with earth clay tiles of different types, over several centuries. Even today with more economical and convenient sheeting materials available for roof cladding, clay tiles are the preferred option especially for domestic dwellings. It has been observed that the production of one such heat sintered pressed clay roof tiles also known as 'Calicut Tiles', results in about 3-4% waste due to various reasons. This waste, generally in the form of broken tiles creates problems of disposing and environmental issues due to generated dust. One area with significant number of tile factories is Waikkala in the Western Province, where over 1000 tons per month of calicut tile waste is estimated to be produced.

Compared with other clay based construction materials, water resistant durable and relatively dense nature of broken Calicut tile particles, makes it a potential candidate as an alternative to coarse aggregate in concrete. As compared to crushed rock aggregate, both density and compressive strength of broken tile particles are substantially low. Therefore, the range of the concrete strengths where successful substitution of coarse aggregate is envisaged should be limited to lower grades of around 20 MPa characteristic compressive strength.

The main aim of this study has been to investigate the possibility of substituting broken Calicut tile particles for natural rock coarse aggregates in lower strength concretes. The lower grades of concrete are generally used for mass concrete screeds, un-reinforced slabs and low axle load concrete road bases.

With the above aim in mind, the following objectives were compiled for this study;

1. Identify a suitable method to transform Calicut tile waste to a grading size suitable for a coarse aggregate.
2. Evaluate physical properties of Calicut Tile Aggregate (CTA).
3. Identify the fresh and hardened concrete properties for nominal mix proportions stipulated by ICTAD with CTA as coarse aggregate.
4. Modify as necessary, the ICTAD & BS stipulated concrete standard mixes to achieve acceptable concrete properties pertaining to envisaged Grade.
5. Assess the financial feasibility of using CTA in concrete.

Major procedure generally adopted in studies of this nature, where substitutive material investigations are involved, is the experimental approach. In order to realize the above objectives following methodology was adopted in this study;

1. Identification of studies through literature review on the use of alternative light weight coarse aggregates, especially pertaining to ranges of material properties and strength.
2. Collection of data on Calicut tile waste generation and identification of a suitable method for the preparation of single sized coarse aggregate from Calicut tile waste.
3. Determination of particle density and water absorption of prepared CTA (according to BS 812 Part 2).
4. Determination of workability and consistency of fresh concrete with CTA as the coarse aggregate, for selected mix proportions.
5. Determination of compressive strength of concrete with CTA as the coarse aggregate, for selected mix proportions.
6. Comparison of cost and benefits of concrete with CTA as the coarse aggregate, and concrete with normal rock as coarse aggregate.

2 REVIEW OF LITERATURE

Essential requirements to be satisfied by an aggregate in concrete are to provide required strength and remain stable within the environment during the service life. The desirable properties of aggregates for concrete have been extensively reviewed in texts on concrete technology such as American Society for Testing Materials (ASTM 1987), Neville (1995), etc. Accordingly, one significant factor contributing to the strength of concrete is its density, which is significantly influenced by the density of the coarse aggregate occupying much of the bulk. Concrete with normal aggregates has a density ranging from 1800-3200 kg/m^3 with an average of 2400 kg/m^3, while concretes with densities <1800 kg/m^3 & >3200 kg/m^3 are considered light weight and heavy weight respectively.

With a bulk density of around 1300 kg/m^3, CTA could be considered as a light weight aggregate. According to Short & Kinniburgh (1978), concretes with compressive strengths exceeding 20 MPa and densities in the range of 1000 – 2000 kg/m^3 have been produced with light weight aggregates. Therefore, possibility of using CTA to produce concretes in the range of 20 MPa characteristic strength is promising if desirable properties in the fresh state could be achieved.

2.1 Studies on Use of Lightweight Materials as Aggregate

Several ad-hoc uses of Calicut tile waste could be observed in the areas where tile production is carried out, such as Waikkala and Wennappuwa. Prominent application observed was the straight forward use as a fill for reclaiming marshy lands. Some other uses such as pot hole filling of rural roads and stacking to form barriers or boundary walls have also been observed. However, no organized study on the use of Calicut tile waste for concrete could be identified from literature.

Use of alternative aggregates for concrete however, has received long term attention of researchers in many countries. A significantly long history of application of by products of production processes such as blast furnace slag, in the production of light weight concrete could be found while some initiatives for the use of glass waste for aggregate were identified in Briton and Ireland. Further, following studies form an interesting background in the study of the use of alternative aggregates derived through the by-products or waste of other processes.

A research by Woon-Kwong Yip & Joo-Hwa Tay (1990) has successfully used the hard residue generated by dried and incinerated municipal waste sludge, broken down to fragments as coarse aggregate for light weight concrete.

A research study by Tommy & Cui (2004) has revealed that a "Green-lightweight" aggregate produced from fly ash and clay could be used to produce structural grade light weight concrete. It is reported that this mix has a high strength, resulting in producing a lightweight concrete with a density of 1590 kg/m^3 and a crushing strength of 34 MPa even though the water absorption of the aggregate is high (13%).It should be noted that, for the same mix proportions, normal weight aggregate concrete gives a crushing strength of no more than 30 MPa.

According to Mir (2001), using low density aggregate types such as Pumice, Vermiculite, Perlite, Herculite and Polystyrene beads lightweight concretes in the region of 800 kg/m3 density could be produced with crushing strengths in the range of 7 – 17 MPa.

2.2 Specifications for Concrete and Constituents

Specifications in the Sri Lankan practice commonly require compliance with requirements of ICTAD-SCA/4/I or the BS 882 for aggregates from natural sources for concrete, ICTAD-SCA/4/I or the BS 5328-Part 1 for specifying concrete and ICTAD-SCA/4/I or the BS 5328-Part 2 specifying concrete mixes. Quality control testing standards for concrete in the fresh as well as hardened state is stipulated by the BS1881.

The BS 882:1992 contains quantitative compliance requirements for particle shape, grading and mechanical properties such as Aggregate Impact Value (AIV). Long term acceptance of this standard in the country has created adequate experience and confidence to justify the validity and sufficiency of these limited requirements. Though the BS 812 which covers the test methods for aggregates gives a wider range of properties to be evaluated, it lacks guidance on interpretation of the test results.

According to ICTAD-SCA/4/I:2004 and BS 5328:1990, concrete could be specified as described below;

Designed Mixes: The mix is specified by required performance in terms of a strength grade, subject to any restriction on materials, range of cement content, maximum allowed free water cement ratio and any other required properties. Strength testing forms an essential part of the assessment of compliance with specification.

Prescribed Mixes: The mix is specified by constituent materials and the properties or quantities of those constituents to produce a concrete with required workability, strength and durability. The assessment of mix proportions forms an essential part of the compliance requirements, so that strength tests are generally not used to assess compliance.

Standard Mixes: The mix is selected from a list of weight based mix proportions, provided by standards and specifications. Standard mix specifications tabulated in ICTAD-SCA/4/I and BS 5328:1990 provides concrete strengths up to 25 MPa and workability in the range of 75 – 125 mm of standard slump.

Nominal Mixes: The mix is generally stipulated in terms of volume based mix proportions. Specified mixes are available for concrete strengths up to 30 MPa. This type of mixes is normally used in small construction operations such as dwelling construction. In Sri Lanka, widest used concrete mixes are Nominal mixes where batching at site is involved.

3 EXPERIMENTAL INVESTIGATION ON CTA BASED CONCRETE

The possibility of total substitution of rock based coarse aggregates in normal concrete mixes with CTA was investigated through an experimental study. For this study both concrete mix proportions for 'Nominal' and 'Standard' mixes were used.

3.1 Constituent Materials for Experimental Concrete Mixes

The main constituent materials for concrete, namely Cement, Aggregate (fine & coarse) and water have to fulfil certain requirements and specifications as stipulated in guidelines and codes of practice. In this study, Ordinary Portland Cement (OPC) conforming to SLS 107 & BS 12 was used throughout with fine aggregate in the form of river sand satisfying the overall grading limits of BS 882:1992 as shown in Table 3.1.

Table 3.1 – Grading of fine aggregate

BS 410 Sieve size (mm)	Percentage by mass passing BS sieve	
	Grading range for fine aggregate (BS 882)	River sand used for this study
10	100	100.0
5	89 – 100	91.0
2.36	60 – 100	76.2
1.18	30 – 100	49.6
0.60	15 – 100	31.8
0.30	5 – 70	14.1
0.15	0 – 15	3.3

Coarse aggregate which is the variable in this study was CTA while normal rock aggregate was used for control tests. Normal rock aggregate used was 20 mm single sized particles derived from gneissic rock. Details on the preparation of CTA and properties are elaborated below.

3.1.1 Preparation of CTA

In the Waikkala area there are about 500 tile factories, which are operational. Broken Calicut tile samples for this study were obtained from three such factories in the area. In the collection of the samples, unburned or surface contaminated waste was excluded. Since 20 mm nominal size aggregate was envisaged for this study, the collected samples needed to be further broken down to this size.

Straight forward manual breaking process was used in the preparation of CTA for this study. This involved fragmenting the tile waste with a mallet to the required size using individual judgement and screening through 28.0 mm sieve. Though the process is labour intensive and slow, wastage and dust generation were low. It was experimentally evaluated that a single labourer could produce about 0.19 m^3 of CTA per hour with less than 7.5% waste.

Mechanical crushing was also investigated by applying waste samples to a jaw crusher set for 20 mm final size. It was noted that by using this method over 40% waste was generated with less than 5 mm particle size with a very high fraction of dust. Therefore, refinement in mechanical crushing through a careful study is required for this method to be adopted in the preparation of CTA. It should be noted that for CTA to be a commercially viable substitute for coarse aggregate, a mechanical mode of crushing should be formulated so that consistent particle size and shape could be obtained.

3.1.2 Particle size distribution of CTA

Physical properties of CTA in the form of particle size distribution and water absorption were measured. Based on the particle size distribution, the produced CTA complied well with the grading limits stipulated for 20 mm single sized aggregates in ICTAD:SCA/4/I :2004 and BS 882:1990 as shown in Table 3.2. An 'immersion in water test' conducted for 30 days with intermediate readings for CTA indicated that a maximum saturation of about 21% moisture content is achieved in 72 hours and 24 hours immersion gives about 17% moisture content which is over 80% of the maximum.

Table 3.2 – Grading of CTA

BS 410 Sieve size (mm)	Percentage by mass passing BS sieve	
	Grading range for 20 mm single size coarse aggregate (BS 882)	CTA
37.5	100	100.0
20.0	89 – 100	96.0
14.0	0 – 70	41.0
10.0	0 – 25	12.0
5.0	0 – 5	0.2

3.1.3 Other relevant physical properties of constituent materials

Several other properties such as Specific gravity and Bulk density are relevant for constituents of a concrete mix especially as the mix proportions are considered both in volume as well as mass. The evaluated physical properties are listed in Table 3.3.

Table 3.3 – Physical Properties of Constituent Materials of Concrete mixes

Constituent Material	Specific gravity	Bulk density (kg/m^3)
Cement		1442
Sand	2.90	1579
CTA	2.11	1307*
Rock aggregate	2.65	1464*

* Measured under Saturated Surface Dry (SSD) condition

3.2 Properties of Experimental Concrete Mixes

The two most important properties of a concrete mix are the workability in the fresh state and the strength in the hardened state. Consequently, the suitability of CTA as coarse aggregate in concrete has to be ascertained by satisfactory compliance of CTA based concretes with accepted requirements and standards. The investigation was initially based on 'Nominal mixes' and extended to 'Standard mixes'.

The procedure adopted in the experimental study was to mix adequate quantities of constituents for each mix proportion to cast four standard concrete cubes with 150 mm sides. Before casting the cubes as stipulated in BS1881, workability was ascertained using the standard slump cone according to BS1881. All mixes were batched by weight, including the Nominal mixes stipulated by volume. Following steps were adopted in general.

- Cement and fine aggregate dry mixed on a flat steel sheet, about 75% of the measured water added and thoroughly mixed to form a uniform paste.
- Coarse aggregate in SSD condition added and mixed with balance water gradually dispensed.
- Slump measured to comply with the expected slump. If less, measured water amounts gradually added until compliance.
- Standard cube moulds (150 mm cube) filled with the concrete in three layers with each layer compacted with 35 blows of 1.8 kg tamper.
- Surface covered cubes de moulded in 24 hours and cured in a water bath until time of testing.
- Cubes tested under compression until crushing failure.

Relevant data recorded at each stage are used for ascertaining compliance according to standards or level of main properties achieved.

3.2.1 Nominal concrete mixes with CTA as coarse aggregate

Most commonly used concrete mixes for general applications in Sri Lanka are the volume batched 'Nominal mixes'. The popularity of this category of mixes mainly comes from the ease with which constituents can be batched (by volume) and the simple ratios used. However, applicability of such mixes is limited by the range of strength grades and workability requirements. Table 3.4 gives the summary details of three nominal mixes with CTA as the coarse aggregate, along with fresh state properties of the mixes. First column of the table also indicates the equivalent grade stipulated by ICTAD:SCA/4/I.

Table 3.4 – Mix Proportions & Fresh State Properties of Three Nominal Mixes with CTA

Mix [Eq. Grade]	Nominal mix proportions (by volume)	Nominal mix proportions (by weight)	w/c ratio	Slump (mm)
M1 [C10]	1 : 3 : 6	1 : 3.29 : 5.44	0.85	75
M2 [C20]	1 : 2 : 4	1 : 2.19 : 3.63	0.75	75
M3 [C25]	1 : 1.5 : 3	1 : 1.64 : 2.72	0.54	125 *

* high slump with low w/c ratio due to higher cement content providing better lubricity.

Standard cubes cast with these concretes were tested in compression with one cube at 7 days and the other three cubes pertaining to one mix in 28 days. These strength test results along with indicated equivalent grade are presented in Table 3.5.

Table 3.5 – Compressive Strength and Grade Compliance of Three Nominal Mixes with CTA

Mix [Eq. Grade]	Compressive strength at 7 days (MPa)	[1]Average Compressive strength at 28 days (MPa)	[2]Target Average Compressive strength at 28 days (MPa)	[2]Achieved intermediate Grade	[2]Achieved Standard Grade
M1 [C10]	5.38	8.28	11	7.28	~ C7.5
M2 [C20]	8.26	15.20	22	14.2	~ C15
M3 [C25]	17.53	25.70	27	23.7	~ C25

[1] Out of three samples [2] According to BS 5328 Part 4:1990

Table 3.5 shows that nominal concrete mixes with CTA are capable of only achieving compliance to a lower grade as compared with normal rock aggregate concrete. Nevertheless, CTA based nominal mixes could be used for the lowered Grades approximately.

3.2.2 Standard concrete mixes with CTA as coarse aggregate

Through the results on nominal mixes, it was evident that good strength as well as workability is achieved when high cement content coupled with higher fraction of fine aggregates is used. Therefore, for the investigation of CTA based concretes using standard mixes, ST4 and ST5 as stipulated in ICTAD:SCA/4/I and BS 5328 were adopted. Standard mixes ST4 and ST5 using normal aggregates have been formulated to produce concretes of Grade 20 and Grade 25, respectively.

Preliminary trial mixes based on fine : coarse aggregate proportions stipulated for ST4 & ST5 indicated lack of cohesion and stability of the mix. Therefore, to circumvent the situation, higher fine aggregate proportions than the stipulated range of 25% -45% by weight, had to be used for the experimental investigation. Thus investigated modified standard mixes were constituted with fine aggregate fraction over 45% by weight. For each of ST4 and ST5 mixes stipulated by both ICTAD and BS guidelines, four mix proportions with fine aggregate content varying from 45% - 60% in 5% increments were investigated, which resulted in 16 different mixes. For each of the mixes, four cubes were cast to be tested in compression.

For all modified mixes 20 mm single sized coarse aggregates were assumed with a higher targeted slump of 125 mm for ST4 and a lower targeted slump of 75 mm for ST5 mixes. Standard cubes cast with these concretes were tested in compression with one cube at 7 days and the other three cubes pertaining to one mix in 28 days. Concrete mix proportions, fresh state workability in terms of slump and crushing strength properties for the modified standard mixes with CTA are given in Table 3.6.

Table 3.6 – Mix Proportions & Fresh State & Strength Properties of Sixteen Standard Mixes with CTA as the coarse aggregate

Standard Mix [Eq. Grade]	Mix No.	Cement (kg/m³)	Total Agg. (kg/m³)	Sand (kg/m³) [%]	CTA (kg/m³) [%]	w/c ratio	Slump (mm)	Comp. strength 7d. (MPa)	Av.Comp. strength 28d. (MPa)
BS-ST4 [C20]	MT1	330	1800	1080[60]	720[40]	0.60	120	9.60	15.27
	MT2			990[55]	810[45]	0.61	125	12.20	16.92
	MT3			**900[50]**	**900[50]**	**0.63**	**130**	**13.07**	**19.29**
	MT4			810[45]	990[55]	0.65	120	12.80	18.32
ICTAD-ST4 [C20]	MT5	350	1750	1050[60]	750[40]	0.65	130	12.09	15.61
	MT6			963[55]	788[45]	0.62	125	11.00	17.12
	MT7			**875[50]**	**875[50]**	**0.58**	**130**	**12.80**	**19.63**
	MT8			788[45]	963[55]	0.55	130	12.40	18.74
BS-ST5 [C25]	MT9	340	1830	1098[60]	732[40]	0.60	95	13.47	21.95
	MT10			1007[55]	824[45]	0.60	90	13.42	21.44
	MT11			**915[50]**	**915[50]**	**0.58**	**90**	**15.91**	**22.25**
	MT12			824[45]	1007[55]	0.55	80	11.40	21.83
ICTAD-ST5 [C25]	MT13	360	1750	1050[60]	700[40]	0.63	90	11.40	19.14
	MT14			963[55]	788[45]	0.60	90	15.70	22.53
	MT15			**875[50]**	**875[50]**	**0.55**	**95**	**16.30**	**23.78**
	MT16			788[45]	963[55]	0.52	100	16.89	22.74

Highlighted mixes exhibited the highest strengths for each standard mix type

It is clearly seen that highest strength values were obtained by the mixes with sand : CTA ratio of 50 : 50. Therefore this ratio could be assumed as the optimum value for modified standard mixes with CTA. In order to compare the workability and strength values obtained with standard mixes containing normal rock coarse aggregates, four mix proportions corresponding to the four standard mix specifications were adopted. Since the surface area of the coarse aggregates in CTA based mixes were indicated to be instrumental in the workability and strength, the sand : rock aggregate ratio was selected so that approximately the same surface area of the CTA counterpart was presented for the mix. For this purpose the weight ratios were selected to result in approximately same volume of CTA in the counterpart mixes. Thus calculated sand : rock aggregate ratio was 44 : 56, since CTA and rock have different bulk densities. These mixes were intended to act as control tests to ascertain the performance of CTA as a substitute for normal rock aggregate. Concrete mix proportions, fresh state workability in terms of slump and crushing strength properties for the modified standard mixes with normal rock aggregate are given in Table 3.7.

Table 3.7 – Mix Proportions & Fresh State & Strength Properties of four Standard Mixes with Normal Rock as the coarse aggregate

Standard Mix [Eq. Grade]	Mix No.	Cement (kg/m^3)	Total Agg. (kg/m^3)	Sand (kg/m^3) [%]	Rock (kg/m^3) [%]	w/c ratio	Slump (mm)	Comp. strength 7d. (MPa)	Av. Comp. strength 28d. (MPa)
BS-ST4 [C20]	MR3	330	1800	792 [44]	1008 [56]	0.62	130	16.20	23.45
ICTAD-ST4 [C20]	MR7	350	1750	770 [44]	980 [56]	0.60	130	15.33	24.59
BS-ST5 [C25]	MR11	340	1830	805 [44]	1025 [56]	0.59	130	17.20	26.52
ICTAD-ST5 [C25]	MR15	360	1750	770 [44]	980 [56]	0.54	125	19.29	28.52

For comparison and ascertaining compliance according to BS 5328 Part 4:1990, the optimum CTA based concrete mix strength results and normal rock based concrete strength results are compiled in Table 3.8. It should be noted that the fresh state workability of all these mixes have satisfied the specification requirements. The first BS 5328 compliance criterion is based on the average of three consecutive cube samples tested at 28 day in compression, not to be less than intended Grade strength plus 2 MPa. The second compliance criterion of the minimum strength result not to be below the intended Grade strength minus 3 MPa, had been satisfied by all investigated mixes.

Table 3.8 – Compressive Strength and Grade Compliance of Modified Standard Mixes with Both CTA and Normal Rock as Coarse Aggregates

Ref. Standard Mix [Eq. Grade]	Mix No.	Compressive strength at 7 days (MPa)	[1]Average Compressive strength at 28 days (MPa)	[2]Target Average Compressive strength at 28 days (MPa)	[2]Achieved intermediate Grade	[2]Achieved Standard Grade
BS-ST4 [C20]	MT3	13.07	19.29	22	17.29	C15
	MR3	16.20	23.45	22	21.45	C20
ICTAD-ST4 [C20]	MT7	12.80	19.63	22	17.63	C15
	MR7	15.33	24.59	22	22.59	C20
BS-ST5 [C25]	MT11	15.91	22.25	27	20.25	C20
	MR11	17.20	26.52	27	24.52	~ C25
ICTAD-ST5 [C25]	MT15	16.30	23.78	27	21.78	C20
	MR15	19.29	28.52	27	26.52	C25

[1] Out of three samples [2] According to BS 5328 Part 4:1990

In Table 3.8 it is shown that modified standard mixes based on normal rock aggregates satisfy the intended grade requirements, while modified standard mixes based on CTA only satisfy one Grade step below. Since modified standard mixes based on ST4 and ST5 satisfy C15 and C20 grades respectively, they could be successfully adopted for lower grade mass concrete applications.

3.3 Cost Comparison of CTA Based Concrete with Conventional Aggregate Concrete

It is of significant interest in a study using an alternative constituent for concrete, to ascertain the economic dimension of the substitution. For the comparison to be realistic, significant properties of the two mixes being compared should be the same, while substituted constituent is the variable parameter. Two mixes, one with CTA (MT15 - Grade C20) and the other with normal rock aggregates (MR3 – Grade C20) were selected for the cost comparison. Further, following assumptions were used in the evaluation.

- Waste Calicut tiles are available from factories at Rs. 100/m^3 and transport cost was not considered.
- Dust generation of 7.5% was assumed in the manual preparation of CTA.
- Skilled and unskilled labour is available for Rs. 1000 and Rs. 800 per day respectively.
- Cement at Rs. 800 per bag, Sand at Rs. 3200/ m^3 and Rock aggregate at Rs. 2800/m^3 were used.

Based on the above, production cost of 1 m^3 of CTA was estimated to be Rs. 708. Then the production cost for 1 m^3 of CTA based MT15 concrete (1 : 2.43 : 2.43 w/w) was estimated to be Rs. 10,070. Similarly, the production cost of normal rock based MR3 concrete (1 : 2.62 : 2.84 w/w) was estimated to be Rs. 11,183. Therefore, as compared with normal aggregate concrete, CTA based concrete indicates a cost saving of about 10%. This indicates that apart from intangible benefits on environment and saving of natural resources, CTA based concretes exhibit a tangible cost benefit too.

4 CONCLUSION

Based on the experimental study, CTA based nominal mixes are only successful for the higher expected strength of Grade 25. The volume batched mix of 1:1.5:3 (Cement : Sand : CTA) fulfilled the compliance requirements for Grade 25 concrete according to ICTAD-SCA/4/I.

CTA based standard mixes ST4 & ST5 (intended for Grade 20 & Grade 25 respectively with normal rock aggregate) could not achieve the targeted strengths. However, modified weigh batched mixes of 1:2.49:3.01 & 1:2.22:2.68 based on ST4 & ST5 fulfilled compliance requirements for Grade 15 & Grade 20 respectively with a significant margin. These modified mixes were achieved with the optimum sand: CTA ratio identified by the experimental study which stood at 1 : 1 by weight. In all above usages of CTA, it is necessary to maintain SSD condition of aggregates

Further, it was identified that, the w/c ratio should be limited to 0.63 for the CTA based Grade 15 concrete, while cement content and total aggregate content are maintained at 330 kg/m^3 and 935 kg/m^3 respectively. Similar consideration for CTA based Grade 20 concrete stipulates that the w/c ratio should be limited to 0.55, while cement content and total aggregate content are maintained at 360 kg/m^3 and 921 kg/m^3 respectively.

In the direct cost comparison of Grade 20 concrete with CTA against normal rock aggregate, 10% saving was indicated. Even though this is seen as a marginal saving, when the indirect benefits due to conservation of good rock aggregates for higher strength concretes, recycling of production waste and reduction of environmental pollution are taken in to account, CTA based concrete for lower grade requirements is a viable proposition.

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