CENTRE FOR MINERALS RESEARCH

Study of effect of process parameters and their interaction in the flotation of UG2 ore

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Declaration

I declare that this thesis, submitted for the degree of Master of Science in Chemical Engineering at the University of Cape Town, is my own work and has not been submitted prior to this for any degree at this university or any other institution.

Signed: Santosh Pani

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SYNOPSIS

Flotation is widely used in the mineral processing industry to extract valuable minerals from the ore. The fundamental steps in this separation process are the attachment of hydrophobic valuable minerals to bubbles, and the subsequent accumulation of the bubble-particle aggregates in the froth phase.

Processing of UG2 ore for concentration of platinum group minerals (PGMs) is a challenging task. UG2 ore contains significant amounts of chromite which is hydrophilic in nature and reports to the concentrate by means of mechanical entrainment. This is a serious problem for the downstream smelting process, which generally has a constraint of 3% chromite. In order to optimise PGM and chromite grade and recovery in UG2 processing, a number of controls are available in a plant. Among the most important are froth height, air flow rate, depressant dosage and frother concentration.

On an individual level, it is expected that an increase in froth height will result in the reduction of the mechanical entrainment of chromite due to an increase in the residence time of air in the froth zone, allowing more drainage of chromite from froth to pulp. High depressant dosage is expected to enhance the grade of PGM and will reduce the recovery of naturally floatable gangue in the concentrate. However, the increase of superficial air velocity will increase the water recovery and solid recovery, thus decreasing the PGM grade with a possible increase in recovery. Increase in frother concentration increases the thickness of bubble lamella and causes more water to flow through the Plateau borders and hence increases the water recovery. Apart from the individual effect of each process parameter the interaction of same play a significant role in the solid and water recovery that affect the chromite content and the PGM grade in the concentrate.

Froth flotation process is a complex process as all the parameters in the flotation interact with each other. The effects of individual parameters are well studied but interactive effects are less documented for UG2 ore flotation. This study investigated the effect of the interaction of the process variables in UG2 ore flotation.

The investigations were carried out in a laboratory column flotation cell for a UG2 ore with a feed size of 60% passing 75 microns. The column flotation cell was useful for studying deep froths at steady state. The column flotation system has distinct advantages over a batch flotation system as it is operated in steady state and open circuit. The steady state continuous process is more relevant than batch process in terms of control and operation. The factorial design of experiments was used for the study of process parameters and their interactions using four variables at two levels. From the factorial design of experiments the regression equations for the responses was developed for assessing the effect of individual as well as the interaction parameters. Guar gum was used as a depressant, Dow 200 is the frother and SIBX was used as a collector in the experiments.

Results showed that the effect of superficial air velocity played an important role for all the responses. There was no interactive effect found for the response of solid recovery while there were individual effects. Solid recovery, water recovery, chrome recovery, chrome grade and PGM recovery were found to be directly proportional to superficial air velocity . Superficial air velocity was inversely proportional to PGM grade. The froth height was the next dominant factor after superficial air velocity for the response of solid recovery, water recovery, chrome recovery and PGM grade. The combined effect of superficial air velocity and froth height played a crucial role in chromite entrainment. The ratio of froth height to superficial air velocity gives the residence time of air in froth zone. Here it was observed that the entrainment decreased with an increase in residence time of air. Entrainment was found to be inversely proportional to the froth residence time of air. The depressant dosage had little effect on solid recovery (mass pull), chrome recovery and PGM grade. It did, however, play a crucial role in the chrome grade. There are interactive effects founds between all the four process parameters for the response of chrome grade. The frother concentration plays a very critical role on every response within the selected range. It was observed that at a wide range of frother concentration (10 ppm to 30 ppm) the effects of frother dominate the other effects for different responses. And when the frother concentration was studied in a narrow range (20ppm to 30ppm) the effect of frother concentration is minimised. The frother concentration has a positive individual effect on water recovery as well as interactive effects with superficial air velocity and depressant dosage. In the response of PGM recovery no significant changes were observed with change in the four parameters compared with PGM grade. The chromite entrainment is a linear function of water recovery which was also evident from this study.

It is concluded that all of the four process parameters investigated superficial air velocity was the dominant parameter in affecting the recovery of chromite and caused a decrease in the grade of PGMs. The depressant dosage had little effect on solid recovery. While it it had a strong influence on chrome grade rather than chrome recovery. The frother concentration had a positive influence water recovery and chrome recovery. The froth height had little effect on PGM recovery but a large effect on chrome recovery for the reduction of mechanical entrainment. The PGM recovery was less affected by changes in the operating conditions than PGM grade. The sensitivity of chrome recovery to superficial air velocity indicated that this parameter should be given careful attention on UG2 operations. Depressant dosage should be low since increased depressant dosage had no effect on mechanical entrainment, but rather increased the grade of chromite and may decrease the valuable mineral recovery. Froth height should be maintained at a maximum level so that the chromite entrainment can be minimized with high PGM grade.

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1 Introduction

In this chapter a general overview of the characteristics of UG2 ore and the factors involving in flotation of UG2 ore is presented. The focus is on effect of physical and chemical parameters on flotation of UG2 ore and problems associated with the flotation of UG2 ore for recovery of PGMs with less entrainment.

1.1 Background

South Africa is the largest producer of platinum in the world (Cawthorn, 1999). About 75% of the world's platinum reserves are present in the Bushveld igneous complex. There are three ore bodies, viz. the Merensky reef, the UG2 reef and the Platreef found in the Bushveld igneous complex. In these three reefs, the platinum group elements (PGEs) are primarily hosted in platinum group minerals (PGMs) that form strong associations with base metal sulphides (especially chalcopyrite, pentlandite and pyrrhotite), and weaker associations with silicate minerals as well as with chromite (McLaren & De Villiers, 1982; Schouwstra et al., 2000).

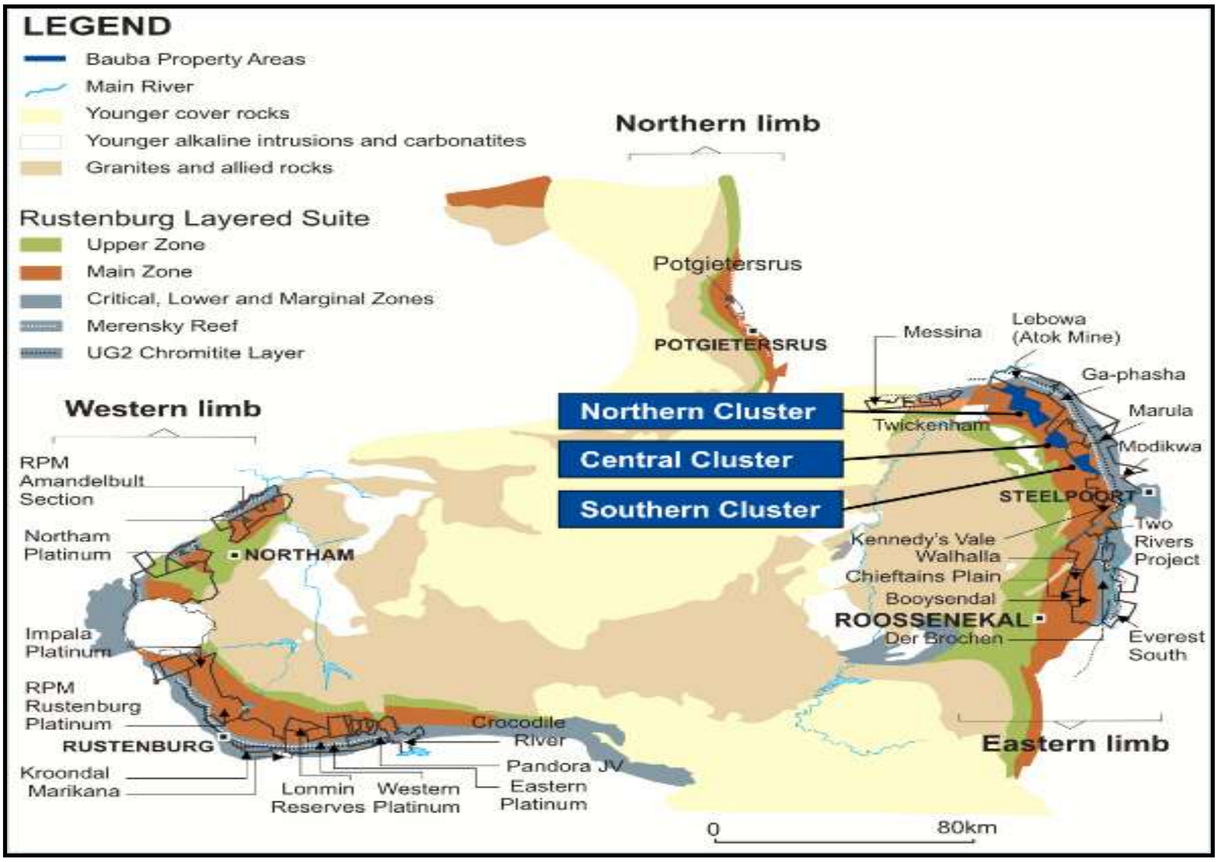


Figure 1.1 Map of the Bushveld Complex

One of the most important ore bodies in this complex is the UG2 ore body which contains platinum group elements and a large amount of non-valuable chromite.

Flotation has been widely employed for the concentration of platinum group minerals from their ore bodies. This process uses the differences in the surface properties of particles to separate the valuable minerals from non-valuable gangue. During processing of UG2 ore it is a challenging task to reduce the chromite entrainment in the concentrate. Chromite is a hydrophilic gangue mineral reporting to the concentrate by entrainment rather than true flotation. Chromite content in the PGM concentrates should be below 3% so that the downstream smelting operation is not negatively affected.

The flotation behaviour of UG2 ore is different from Merensky reef ore as the former is dominated with hydrophilic chromite gangue. The important reagent dosages considered for the froth flotation are collector, frother and depressant dosages and their types. Frother concentration has an effect on PGM recovery and entrainment. Adequate frother concentration is required to stabilize the air-water interface and reduce the bubble size. The process parameters like froth height, superficial air velocity and frother concentration all play a major role in the froth recovery which is indicated by water recovery. As already stated, in the case of UG2 ore the hydrophilic chromite mineral reports to the concentrate by mechanical entertainment rather than true flotation. The mechanical entrainment of gangue minerals usually has a linear relationship to water recovery (Engelbrecht & Woodburn, 1975; Bishop & White, 1976). The froth height can be varied significantly if a column flotation cell is used. If the froth height and superficial air velocity are increased in the column, the residence time of the air will increase resulting in a lower carryover of gangue minerals to the froth phase (Bishop & White, 1976; Savassi et al., 1998). As the UG2 ore also contains orthopyroxinates associated with naturally floatable gangue mineral like talc, depressant dosage will also have an effect on the recovery of naturally floatable gangue.

Many researchers have studied the flotation of UG2 ore using a classical method where the effect of single parameter is investigated while keeping the other parameters constant (Ekmekci et al., 2003; Valenta, 2007). Since flotation is a complex phenomenon it is important to take into account the interactive effects among the process parameters and how these interactions play a critical role in the recovery of PGMs and the entrainment of chromite.

The present investigations were carried out in a laboratory open circuit column flotation cell operating at steady state. The flotation feed size was 60% passing 75 microns. The interactions investigated were those between superficial air velocity, froth height, depressant dosages and frother concentration. The column flotation cell is useful for this investigation as it enables a wide range of froth heights to be used. The continuous column flotation system also has distinct advantages over a batch flotation system as it is operated in steady state and in open circuit. Data from a steady state continuous system is more easily analyzed compared to the unsteady state batch system.

A factorial design of experiments approach was used to study the effect of the various process parameters. It was predicted that the reduction of the mechanical entrainment of chromite in flotation process could be achieved by increasing the froth height since this would increase the residence time of hydrophobic particles in the froth zone resulting in more drainage of chromite from the froth to pulp zone. A high depressant dosage was expected to enhance the grade of PGMs and a reduction in the recovery of solids and water recovery. However this reduction in solids recovery could also destabilize the froth. The increase in superficial air velocity was expected to increase the water and solids recovery. An increase in frother concentration was expected to increase water recovery by increasing the thickness of lamella thus causing more water to flow through the plateau borders. Apart from the individual effect of each process parameter it was important to determine if the interaction of these played a significant role in the solids and water recovery which could affect the chromite recovery and the PGM grade of the concentrate. Using a factorial design of experiments the regression equations for the responses was developed for assessing the effect of individual as well as the interaction parameters.

1.2 Objectives

This study investigated the interactive effects between the following process parameters by determining their respective responses during flotation.

- Water recovery
- Solid recovery
- Chromite recovery
- Chromite grade
- PGM recovery
- PGM grade

1.3 Structure of Thesis

Chapter 1 reviews the flotation process and presents the objectives of the research. Chapter 2 presents the literature review which is divided into five parts: flotation principles, column flotation, UG2 ore, mechanical entrainment, effect of factors on froth flotation and finally the factorial design.

Chapter 3 describes the experimental procedures and measurement techniques.

Chapter 4 presents the results obtained .

Chapter 5 discusses these results, providing mechanistic arguments and quantitative interpretations of each factor and their interactions as determined using a factorial design approach.

Chapter 6 presents the conclusions and proposes future work that may be undertaken.

2 Literature Review

2.1 Froth Flotation Principles

Froth flotation is a highly versatile technique used in the mineral processing industry for concentration of the minerals from their ores. It is an important process for the recovery of valuable minerals in mineral processing industries (Fuerstenau, 1976). It is estimated that around two billion tonnes of ore has been treated by froth flotation (Pearse, 2005). Flotation is a separation process used to separate mineral particles having different hydrophobicities from gangue by altering the surface properties (Wills, 2006). Hydrophobicity indicates the preference for a particle to move from the water phase to the gas phase, i.e. the air bubble. In mineral processing, solids which can be easily wetted with water are called hydrophilic, while solids with limited affinity for wetting are called hydrophobic. As a result of hydrophobicity, particles adhere to a gas bubble forming a particle-bubble aggregate which is lighter than water, and travels upward to the pulp-froth interface as shown in Figure 2.1 (Drzymala, 2007). Hydrophilic particles do not adhere to the bubbles and report to the tailings.

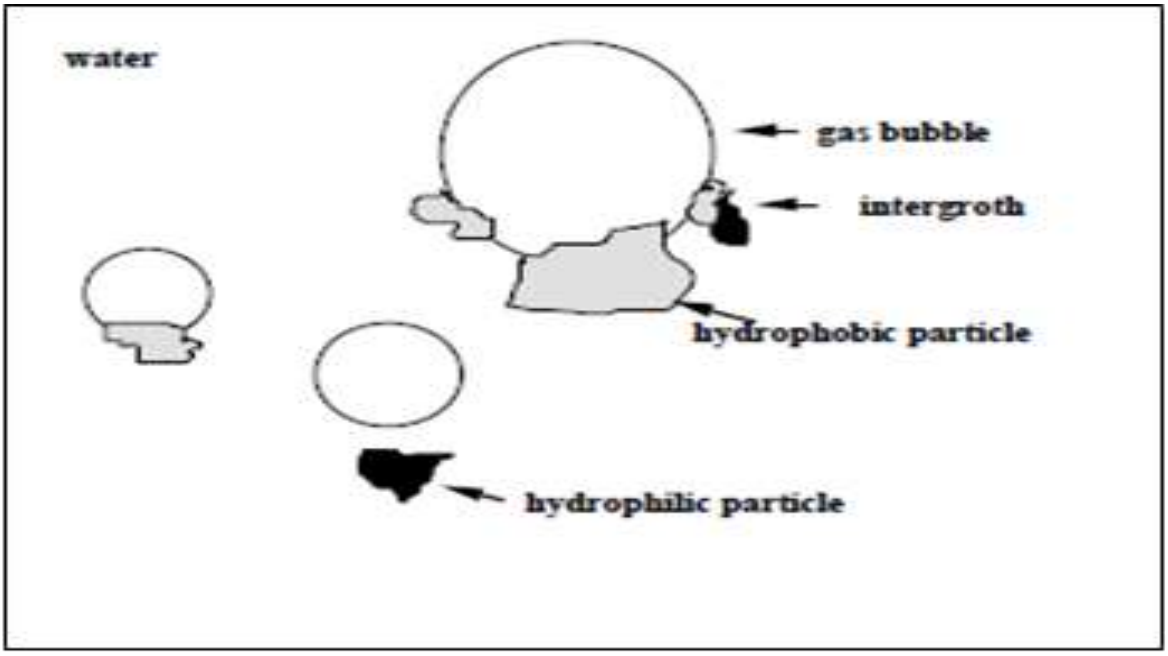


Figure 2.1 Froth flotation process in terms of hydrophobicity (Drzymala, 2007)

Froth flotation process is a consequence of different sub processes acting together in a three phase system in water (Polat et al., 2003). The steps involved in the process include interaction of particles with the surface active reagent, called collector, to increase the hydrophobicity of the particles, attachment of hydrophobic particles to the rising air bubbles, detachment of less hydrophobic minerals from the bubbles (Whelan & Brown, 1956) and finally the mineralised air bubbles form a structure on the surface of the pulp called froth. Surfactant called frother is used to form a stabilised bubble and froth.

A large number of physical and chemical parameters involves in the froth flotation process. According to a study carried out by Klimpel (1984) these parameters were classified into three groups as shown in Figure 2.2. The primary focus of this research work is to study the effect of process parameters on the froth flotation process.

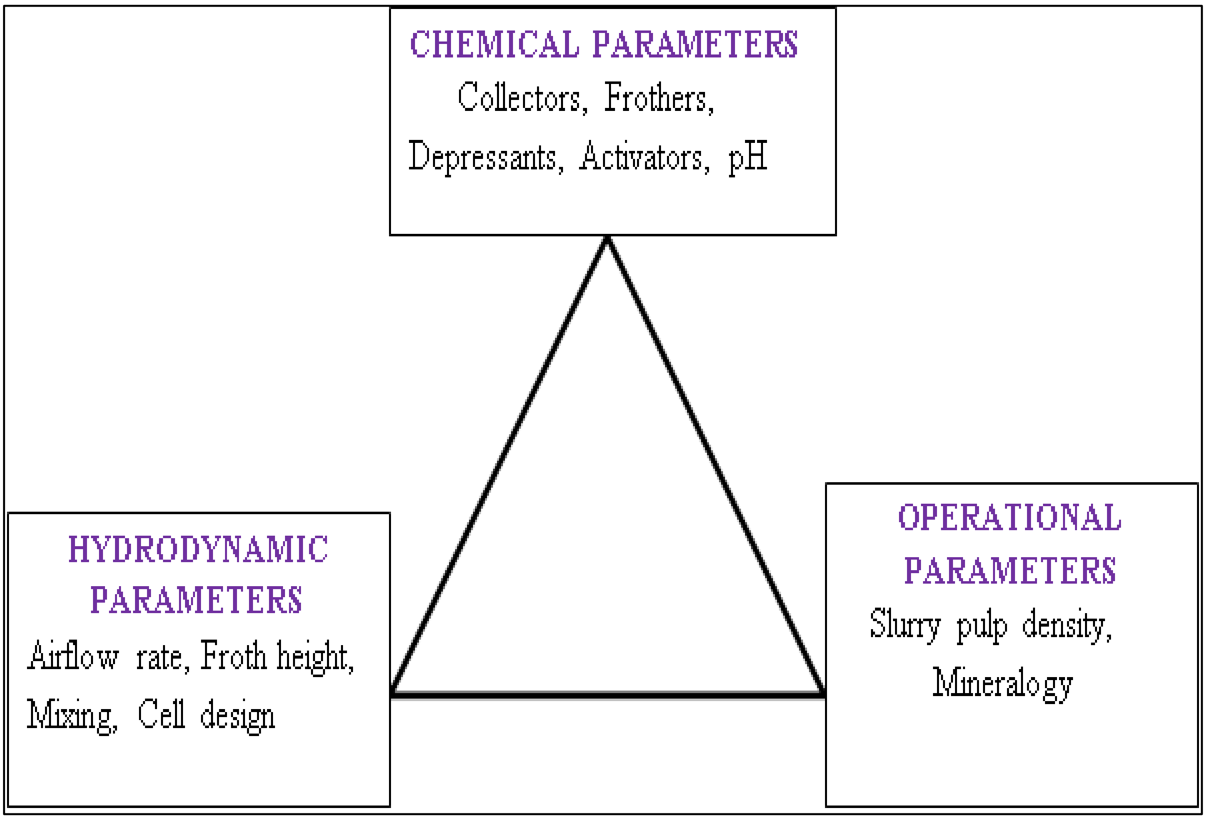


Figure 2.2 Factors involved in the flotation system (Klimpel, 1984)

2.2 Why Column Flotation

Column flotation is a technique developed in early 60’s for the processing of fine particles (Boutin & Wheeler, 1967). Some of the hydrophilic gangue minerals report to the concentrate by means of mechanical entrainment during flotation. All these processes occur in froth zone. To overcome the mechanical entrainment and improvement of selectivity, column flotation is employed for the froth flotation purposes (Dobby & Finch, 1985;Yianatos et al., 1988).

Therefore for effective study of froth zone, a column is ideal since a deeper froth can be maintained than in a batch flotation cell.In addition, the column flotation cell is continuously operated unlike the batch cell (Coffin & Miszczak, 1982; Wheeler, 1985; Finch & Dobby, 1990). The distinctions between the conventional mechanical cell and flotation column are given in Table 2.1.

Table 2.1 Comparison of column flotation with mechanical cell (Sastri, 1998)

Mechanical Cells	Flotation Column
Similar to ideal mixers	Operate under conditions of plug flow with varying degrees of axial dispersion
Air bubbles are formed by a rotating impeller	Air bubbles are formed by passing compressed air/air slurry mixture through a bubble generator
Relative velocity between air bubbles and mineral particles is negligible except near the impeller.	The relative velocity between bubbles and mineral particles is high throughout the column.
At any given time only a small fraction of the mineral particles are in the vicinity of air bubbles. Thus effective residence time is reduced compared to the total residence time of the cell.	Total length of collection zone is available for collision and attachment. Thus total residence time of particles can be effectively utilized.
Highly turbulent conditions promote i) detachment of once attached particles and ii) contamination of froth by entrainment of non-floatable particles	The quiescent operation results in i) reduced possibility of detachment and ii) reduction in entrainment of gangue minerals in the froth
Flotation of relatively large size bubbles, fine particles are difficult to float	Relatively smaller bubbles give higher surface and higher residence times.

In the present investigation, the column that was used in the experiments was an in-line aerated column. Here by using the in-line aerated column the effect of parameters such as froth depth can be effectively studied as it enables quite different froth depths to be used (Xu et al., 1996). The main difference between the conventional column and the in-line aerated column is that the feed and air are mixed together prior to being fed into the bottom of the column (Xu et al., 1996). In the in- line aerated column the slurry and air bubbles move co-currently with each other. The layout of the in- line aerated column used in this study is shown in Figure 2.3 adopted from Xu et al., 1996.

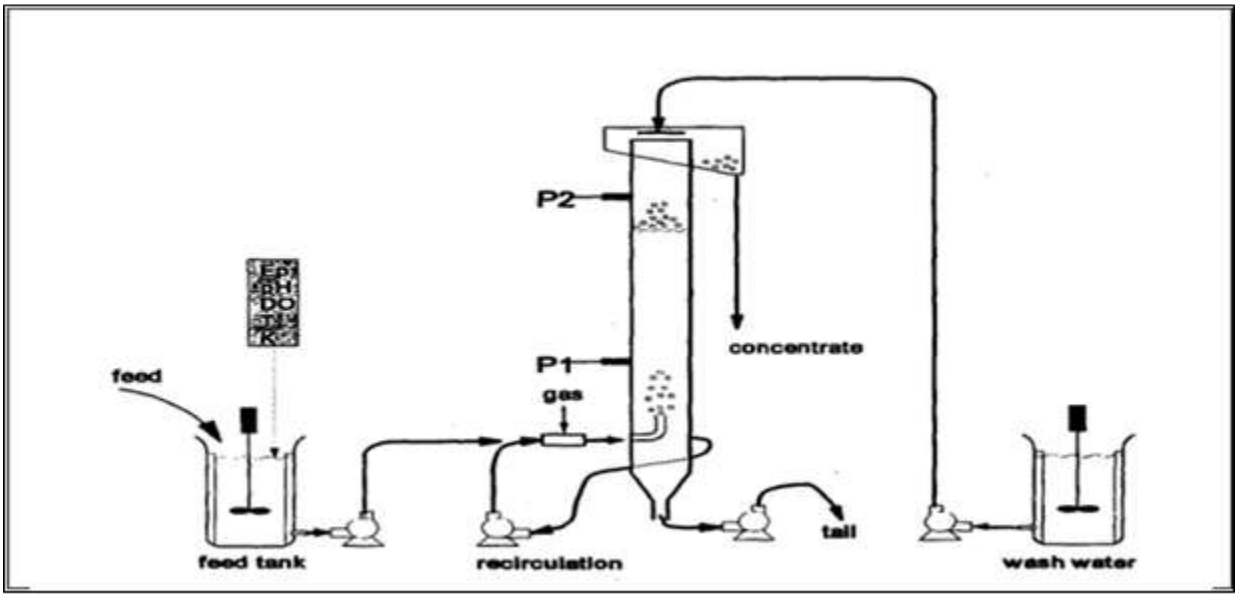


Figure 2.3 Schematics of the inline aerated column adapted from (Xu, et al., 1996)

2.3 Ore

2.3.1 UG2 Ore Body and Geology

South Africa is the largest producer of platinum in the world. About 75% of the world's platinum reserves are present in the Bushveld Igneous Complex (BIC). There are three different ore bodies namely Merensky reef, UG2 chromite and Platreef (Cawthorn, 1999). The Merensky reef and UG2 can be found on the surface over 300 kilometres in two different arcs while Platreef is spread over 30kms. The Merensky reef was the sole source of platinum until 1970. Thereafter Lonmin began the mining of UG2 ore followed by other companies (Cawthorn, 1999). Presently UG2 ore body is known as one of the largest reserves of Platinum Group Minerals (PGMs) in the world (Cawthorn, 1999).The UG2 ore body is a platinum bearing chromite layer present in the Bushveld complex of South Africa (McLaren

& De Villiers, 1982).The chromite layers of Bushveld complex are present in the critical zone (Mondal & Mathez, 2007) and are subdivided into three sub groups known as lower (LG), middle (MG) and upper group (UG) according to their height in the zone (Eales, 2000). The UG2 ore body therefore represents the second layer of the upper group and lies between 20 to 400 meters under the Merensky reef (Schouwstra et al., 2000). The composition of some common minerals of Bushveld complex is shown in Table 2.2 (Schouwstra et al., 2000).

Table 2.2 The composition of some common minerals of Bushveld complex

Mineral Group	**Mineral**	**Major Composition**
Pyroxine	Enstatite	Mg, Fe silicate
	Augite	Mg, Fe, Ca silicate
Feldspar	Plagioclase	Ca, Na, Al silicate
Mica	Phlogopite	K, Mg, Al silicate
	Biotite	K, Mg, Fe, Al silicate
Chlorite	Chlorite	Hydrated Mg, Fe, Al silicate
Clay	Talc	Hydrated Mg silicate
Serpentine	Serpentine	Hydrated Mg, Fe silicate
Spinel	Chromite	Cr, Fe, Mg oxide
	Pentlandite	Ni, Fe sulphide
Sulphide	Chalcopyrite	Cu, Fe sulphide
	Pyrrohotite	Fe mono-sulphide
	Pyrite	Fe di-sulphide

2.3.2 Ore Characteristic

The concentration of PGEs in the UG2 ore body is typically about 4-7 g/t, and consists of 60-90% chromitite (Schouwstra et al., 2000). The platinum group minerals can be associated with base sulphide minerals such as chalcopyrite, pyrrhotite, pyrite, pentlandite and some millerite, which are found in trace amount, less than 0.1 %. The most common PGE sulphides are laurite, cooperite, malarite, braggite and vystokite and the gangue minerals are typically chromite and silicate (Cawthorn, 1999; Penberthy et al., 2000). Other minerals present in low concentrations (<5%) are the silicates like phlogopite and biotite, the oxides (ilmenite, rutile and magnetite); quartz, serpentine and talc. Depending on the type and characteristic of the ore, platinum group assemblages could be predominantly sulphide minerals, with some non-sulphide minerals.

2.3.3 Response of UG2 ore to Froth Flotation

The PGMs of UG2 ore are concentrated by froth flotation. Generally PGM minerals are completely liberated at a very fine size such as 7 to 10μm in case of UG2 ore. Therefore, very fine grinding is required prior to UG2 ore flotation to liberate the valuable minerals. However in the ultrafine size the probability of mechanical entrainment of gangue minerals increases. UG2 ore contains significant amount of chromite which is believed to be recovered by entrainment. High grades chromites have severe adverse effect in the smelting process of PGM extraction since the smelters have a cut off limit of chromite of 3% (Ekemci et al., 2003). To overcome the problem of entrainment two stage grinding and cleaning process is employed for the concentration of PGMs in the UG2 ore. The PGM recovery from UG2 ore through the Bushveld Complex varies from 75% to +90% (Valenta, 2007). The typical PGM supply chain is given below in Figure 2.4

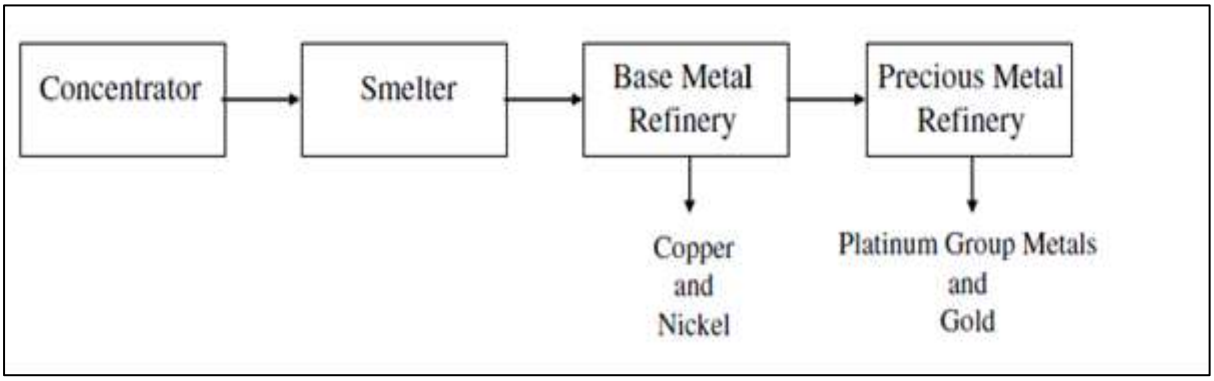


Figure 2.4 Typical PGM supply chain (Valenta, 2007)

The PGM minerals are concentrated by froth flotation in concentrator and then go for smelting for recovery of base metal sulphides and PGMs. After refining of base metals the precious metals are refined. In the smelting operation the excess chromite causes problems in smelting. The challenge in UG2 ore processing is to produce a concentrate having low grade chromite. The UG2 ore consists of two major different gangue minerals such as chromite and pyroxenes with different characteristics. The typical flow sheet for processing of UG2 ore employed in the concentration process is given in Figure 2.5 (Valenta, 2007)

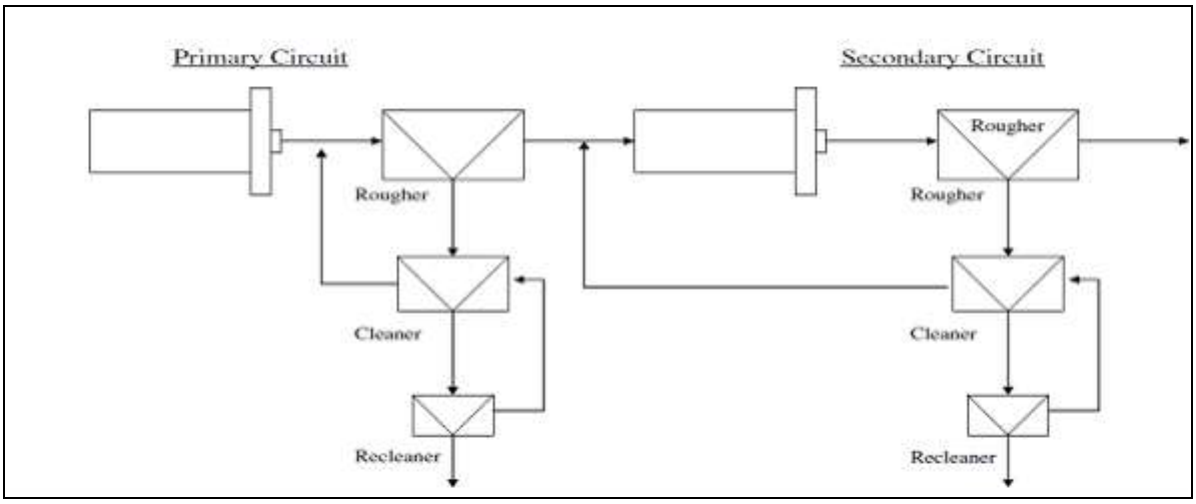


Figure 2.5 Typical UG2 ore processing flow sheet (Valenta, 2007)

2.3.4 Mechanical entrainment in UG2 ore Flotation

Mechanical entrainment in froth flotation process is defined as the unwanted carryover of non-floatable gangue minerals from pulp zone to froth zone. In flotation process the valuable minerals attach to the rising bubbles and are recovered in the concentrates and hydrophilic gangue minerals report to the tailing stream. However, in actual practice there are always some gangue minerals which report to the concentrates along with the valuable minerals. The process is represented in Figure 2.6.

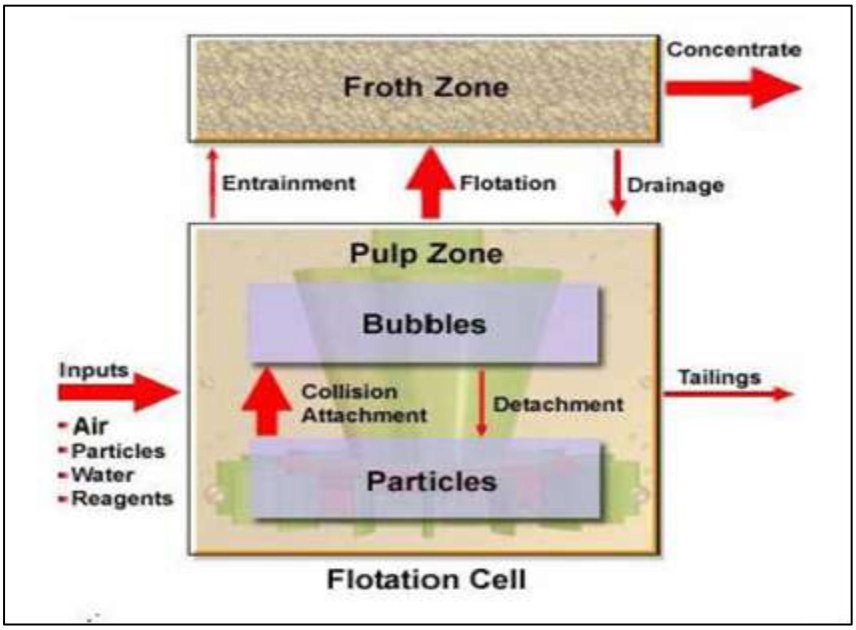


Figure 2.6 Froth flotation process (Bradshaw, 2012)

In the above figure two distinct zones in the froth flotation process, viz. the froth zone and the pulp zone are shown. In the pulp zones the mineralized bubbles attached to the rising air bubbles and report to the froth zone. The functions of the froth phase in turn are to (i) transport the mineral laden bubble from the pulp-froth interface to the concentrate launder and (ii) promote further separation of hydrophobic from hydrophilic particles by the gravity drainage of gangue-bearing water back to the pulp phase (Nguyen and Schulze, 2004).The unwanted carryover of gangue minerals also happens in the process. This process of unwanted carryover is called mechanical entrainment.

Livshits & Bezrodnaya (1961) and Jowett (1966) have studied the factors which affect the recovery of entrained gangue. They showed that these include particle size, pulp density and the amount of recovered water. Johnson et al., (1974) showed that entrainment is strongly dependent on water recovery, particle size and density of the gangue minerals present in the ore. Mechanical entrainment is a non-selective process and is independent of particle surface properties (Trahar, 1981). Water flow is the medium whereby gangue is transported by mechanical entrainment (Harris et al., 1963; Jowett, 1966; Sadler III, 1973; Engelbrecht & Woodbum, 1975; Bisshop & White, 1976). The mechanical entrainment of gangue minerals is described by the mechanisms such as boundary layer theory (Gaudin, 1957; Moys, 1978), bubble wake theory and bubble swarm theory (Smith & Warren, 1989). Engelbrecht and Woodburn (1975) showed that mechanical entrainment of gangue follows a linear relationship with recovery of water. Figure 2.7 shows the recovery of silica gangue as a function of water recovery (Engelbrecht & Woodburn, 1975).

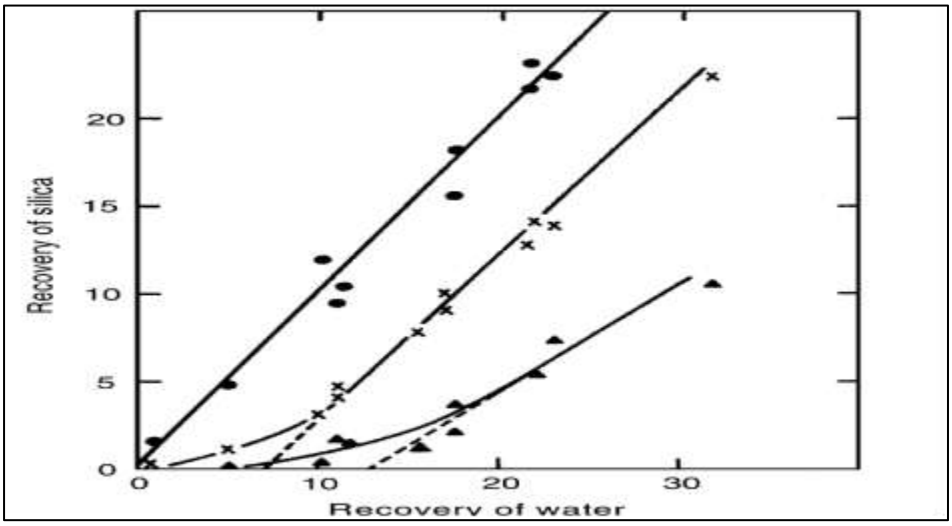


Figure 2.7 Recovery of silica gangue as a function of water recovery (Engelbrecht & Woodburn, 1975)

Kirjavanien (1992) also showed that mechanical entrainment follows a linear relationship with water recovery and the entrainment is expressed as a term known as entrainment factor. The entrainment factor is a function of parameters such as water recovery, slurry viscosity and particle mass. The model developed by Kirjavanien (1992) is given below in equation 2.1 to show the dependency of entrainment factor on various responses and factors.

$$P = \frac{W^{0.7}}{W^{0.7} + b\psi\eta^{-0.5\psi}m^{0.5\psi^{-0.4}}} \tag{2.1}$$

Where P= entrainment factor, W= water recovery rate (kg/m^{2}sec), m =particle mass,

η= slurry viscosity, ψ= dynamic shape factor and b= a constant

2.4 Effect of Process Parameters on Flotation Performances

There are a number of factors affecting the performance of a flotation process. These are generally classified as physical and chemical factors. In the current study of UG2 ore the main focus will be on the following physical factors, viz. Froth height, airflow rate and chemical factors, viz. depressant dosage and frother concentration.

2.4.1 Chemical Parameters

There are several chemical factors such as type and dosage of collector, depressant activator and frother employed in a froth flotation process. In case of UG2 ore flotation the major chemical parameters which were studied in this work were depressant dosage and frother concentration.

2.4.1.1 *Effect of Depressant Dosage*

The role of depressant in froth flotation is to depress the hydrophilic gangue minerals and increase the grade of the recovered product, i.e. it is to inhibit flotation of a given mineral (Laskowski & Pugh, 1992). The primary requirements of depressants used in gangue depression are given below (Fuerstenau et al.,2007).

(i) Must have functional groups that exhibit preferential attraction to the gangue minerals.

(ii) Must have a strongly hydrophilic character by virtue of either the same or other functional groups in the molecular structure and

(iii) They should not possess functional groups that compete effectively with the collector for the surface of the minerals which are to be floated.

The polymeric depressants typically used in PGM flotation applications are either modified guar gum or carboxymethyl cellulose (CMC) (Bradshaw et al., 2005; Corin, 2010). The UG2 ore contains naturally floatable talc and guar gum and CMC are good depressants for depressing talc (Rath et al., 1997). The major difference between them is that CMC ionises in solution and it is negatively charged while guar is only slightly charged (Mackenzie, 1986). CMC molecules therefore, once adsorbed onto gangue minerals, cause these minerals to become negatively charged and, particularly at high dosages, they therefore tend to repel each other. Guar gum is a branched polysaccharide with galactomannan forming the basic unit (Figure 2.8). The hydroxyl groups are arranged in a cis-configuration on the C-2 and C-3 atoms. Thus the guar gum has been found to be stronger depressant of naturally floating gangue than CMC at low dosages (Wiese, 2009). High depressant dosage increases the grade and decreases the recovery of the concentrates (Wiese et al., 2010).

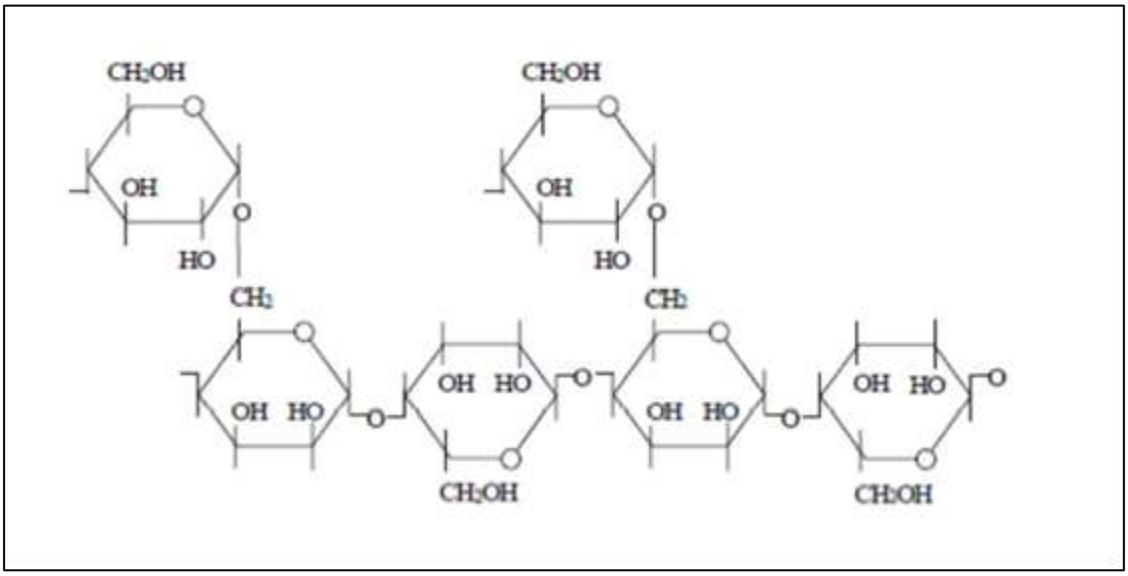


Figure 2.8 Structure of Guar gum molecule

The effect of depressant plays a role on water recovery (Wiese et al., 2011). The amount of water recovery decreases with increase in depressant dosage. High depressant dosage may result in a destabilized froth and lower recoveries (Wiese, 2009; Wiese et al., 2011), as a result of less solids reporting to the froth phase. Valenta (2007) in his studies on processing of UG2 ore showed that the depressant dosage has very little effect on recovery of chromite but had a significant effect on chromite grade possibly because of the effect of the depressant on the recovery of gangue minerals

2.4.1.2 Effect of Frother Concentration

Frothers are neutral molecules made up of a hydrocarbon chain and a polar end-group (Pearse, 2005). The hydrocarbon group can be straight, branched or cyclic whilst the polar group can be a hydroxyl, carbonyl, ester, carboxyl, amine, nitrile, phosphate or sulphate. The molecule, due to its heteropolar structure, is surface-active and preferentially adsorbs at the air-water interface with the hydrocarbon chain preferring the air-side and the polar group preferring the water-side where it undergoes hydrogen bonding with water molecules as shown in Figure 2.9 (Laskowski, 1993).Thus, frothers keep air bubbles dispersed and prevents their coalescence (Wills, 2006). In case of mineral flotation it is commonly believed that, if the frother dosage increases, there is an increase in water recovery. Water transport is influenced by the bubble size or more precisely the bubble surface area flux (Finch and Dobby, 1990). High frother concentration leads to a stable froth. The behaviour of flotation froths is controlled by the properties of the frother molecules at the air/water interface.

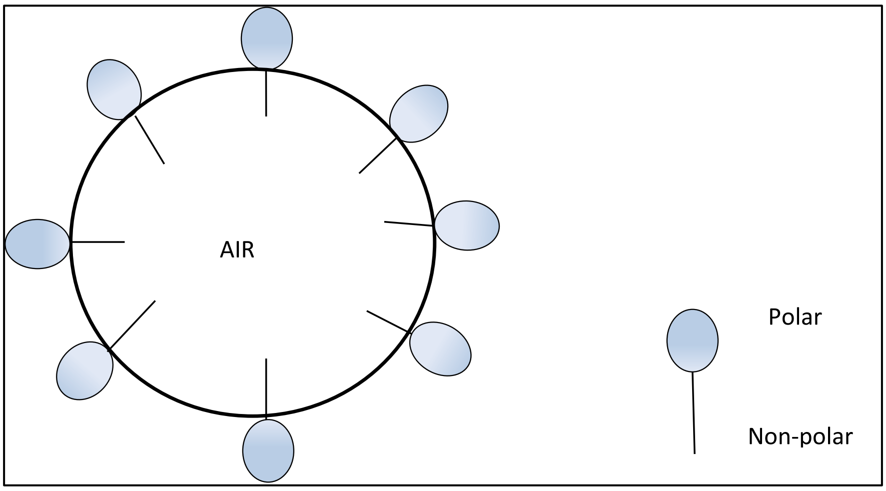


Figure 2.9 Working principle of frother molecule

This interface becomes visco-elastic, more immobile and increasingly stable when increased amounts of frother molecules are adsorbed at the air/water interface. The ultimate effect is that liquid drainage from the lamellae is retarded and hence, bubble coalescence is inhibited. The overall effect is that froth stability is increased with increasing frother concentration (Langevin, 2000). This is due to the Gibbs-Marangoni effect which suggests that if the lamellae are thinned, then the concentration of frother molecules at the interface is disturbed from its equilibrium concentration. Therefore, if excess frother molecules are present in the pulp, these will migrate to the interface and thus restore the equilibrium concentration resulting in more water being pulled in to increase the film thickness. If water recovery increases, there is more solid recovery due to the stable froth which reduces selectivity and leads to a non-selective entrainment (Yoon & Luterell, 1989).

In a study of the effect of frother concentration it was shown that frother addition has an effect on water recovery as shown in Figure 2.10 (Wiese et al., 2012). The tests were conducted using two different types of frothers to compare the water recovery in the absence of solids (Figure 2.10). Increase in frother concentration also leads to smaller bubble generation and enhances the recovery. In general small bubbles resulting from increasing frother concentration produces a stable thick froth (Goodall & O'Connor, 1991).

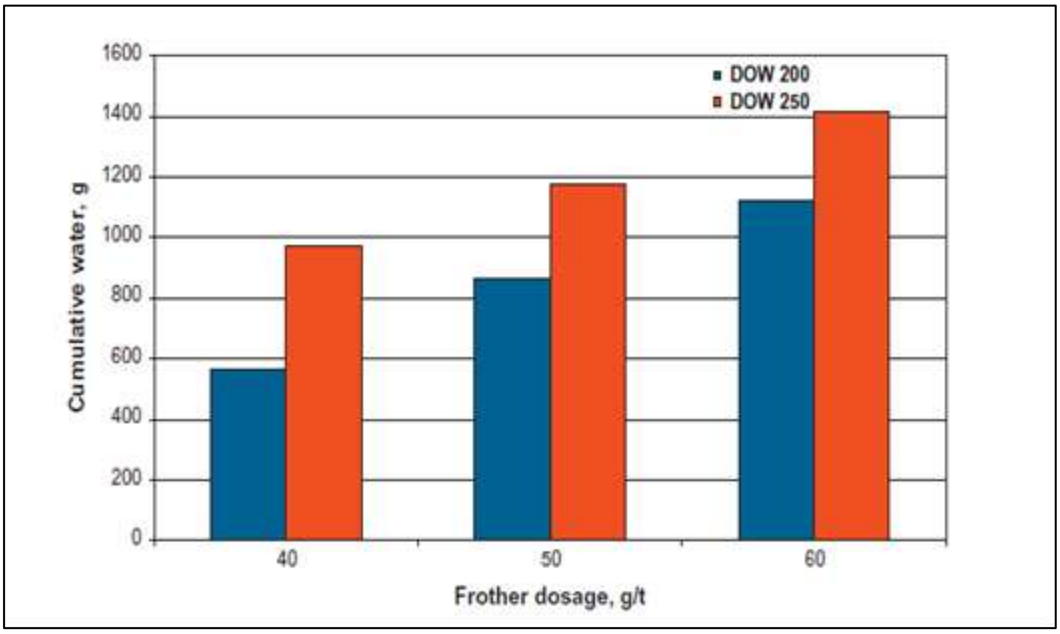


Figure 2.10 Effect of frother concentration on water recovery in a two phase system (Wiese et al., 2012)

2.4.2 Effect of Physical Parameters

The two most common levers available to plant operators to manage the grade and recovery are the air flow rate and froth depth. These will be discussed in the following sections.

2.4.2.1 Effect of Froth Height

The recovery of fine particles can be reduced considerably using the column flotation cell as different froth depths can be adjusted (Finch et al., 1989). According to a model developed by Neethling and Cilliers (2002), mechanical entrainment is a complex mechanism and is caused by changes in froth residence time, froth structure and froth properties. For increasing the particle residence time, froth height is maintained in the froth zone. The fundamental action that influences flotation is the attachment of hydrophobic particles onto the bubbles in the collecting zone. In a study by Ekemci et al., 2003, it was suggested that by increasing the froth height the mechanical entrainment of chromite could be reduced.

2.4.2.2 Effect of Superficial Air Velocity

In column flotation air is fed into the bottom of the column resulting in the production of bubbles in the collection zone. These air bubbles rise through the pulp, attracting hydrophobic particles which are eventually recovered in the launder. The parameters that describe the dispersion of gas in flotation systems are the superficial gas velocity or gas rate (J_g), gas hold up (ε_g), bubble size (D_b) and the bubble surface area flux (S_b) (Finch et al., 2007). The relationship between the gas hold up and gas rate is used as a basis for hydrodynamic characterization. The gas rate and gas holdup is shown in Equation 2.2 and Figure 2.11 (Sastri, 1998)

$$S_b = 6\frac{J_g}{D_b} \tag{2.2}$$

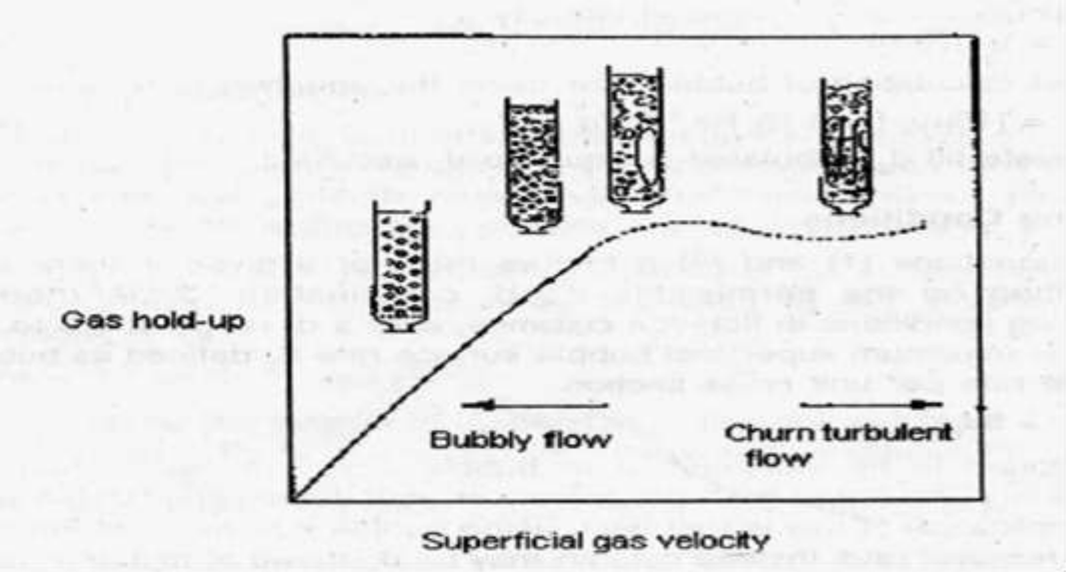


Figure 2.11 Relationship between gas hold up and gas rate showing the two principle flow regions (Sastri, 1998)

In a laminar flow region the bubbles produced are of a uniform size and they rise through the pulp at uniform velocity. By comparison, turbulent flow produces larger bubbles which rapidly ascend through the collection zone displacing slurry and fine bubbles downwards (Finch et al., 2007).

At high shear and turbulence rates fine particles can easily collide with the bubbles produced, however for coarse particles there is a higher probability of a detachment of particles from the bubble surface (Schulze, 1984). A large amount of gas also causes a reduction in the grade and recovery of the concentrate. According to Hadler et al. (2006), it was found that there was a drop in air recovery with increasing air flow rate due to lower froth stability. This resulted a lower PGM recovery.

Here the bubble swarm mechanism plays a role for the recovery of gangue minerals. The mechanical entrainment of the gangue minerals also depend upon the residence time of air in the froth zone (Savassi et al., 1998). The froth residence time of the air depends upon the froth height and the superficial air velocity in the equation given below in equation 2.3.

$$\lambda_{air} = \frac{h}{J_g} \tag{2.3}$$

where λ_{air} = residence time of air in froth zone in sec., h= froth height in cm and J_g= superficial air velocity in cm/sec. If the froth residence time of the air increases then there is an decrease in solid recovery and decrease in gangue recovery.

2.4.3 Interactive Effects of the Parameters

There are always some interactive effects of process parameters on grade and recovery of minerals. Little work so far has been carried out on the interactive effects in the flotation of UG2 ore. Savassi et al., (1998) studied the combined effect of superficial air velocity and froth depth on water recovery and mechanical entrainment. They found that the mechanical entrainment is a function of residence time of air in the froth zone as shown in Figure 2.12 (Savassi et al., 1998)

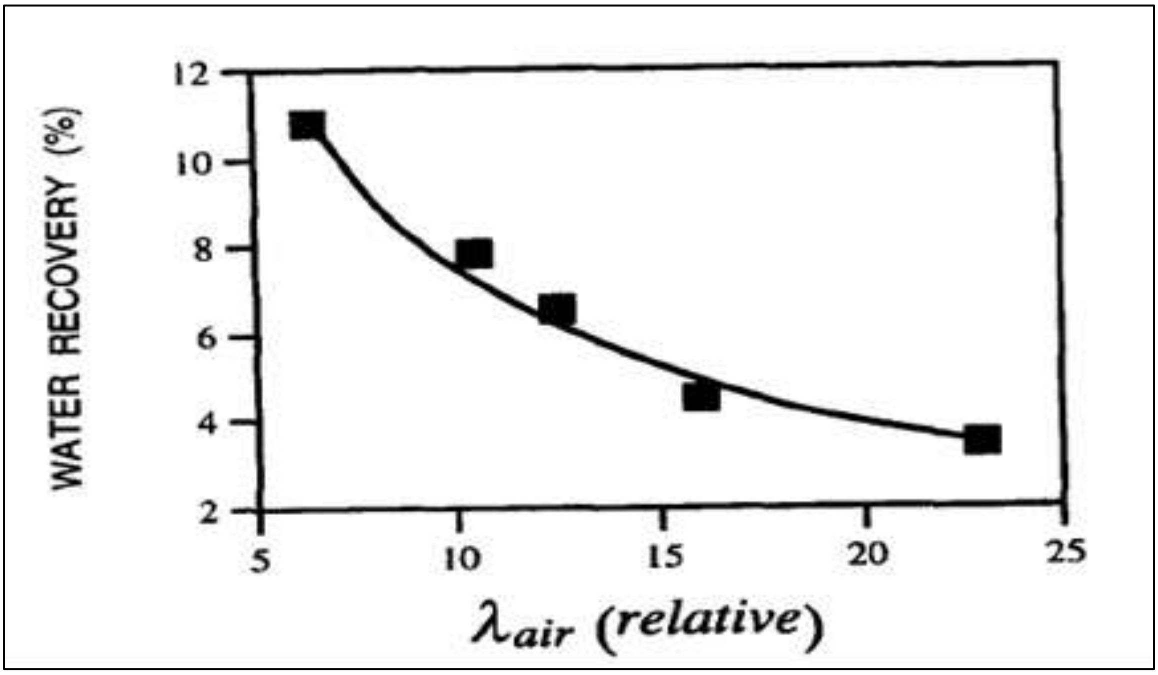


Figure 2.12 Water recovery as a function of froth residence time of air

They had also developed a model relating water recovery and froth residence time of air suggesting that water recovery and entrainment are proportional to the froth residence time of air. The models are given below in equation 2.4 and 2.5.

$$\xi = -0.667\lambda_{air} + 40.416 \tag{2.4}$$

$$R_{Fw} = 63.905\lambda_{air}^{-0.926} \tag{2.5}$$

Where ξ is the entrainment factor R_{Fw} is the recovery of water by the froth. From the equations (2.4) and (2.5) it can be clearly seen that froth height and superficial air velocity have a combined effect on water recovery and hydrophilic entrainment.

Wiese et al, (2012) studied the combined effect of frother and depressant dosage as shown in Figure 2.13 . At high depressant dosage and high frother concentration there is a decrease in solids recovery while there is an increase in water recovery. But if we compare the case of low or no depressant dosage with high depressant dosage then there is a decrease in solid recovery but the water recovery is similar for both the cases. So it may attributed that the effect of frother concentration is more prominent than depressant dosage for water rrecovery.

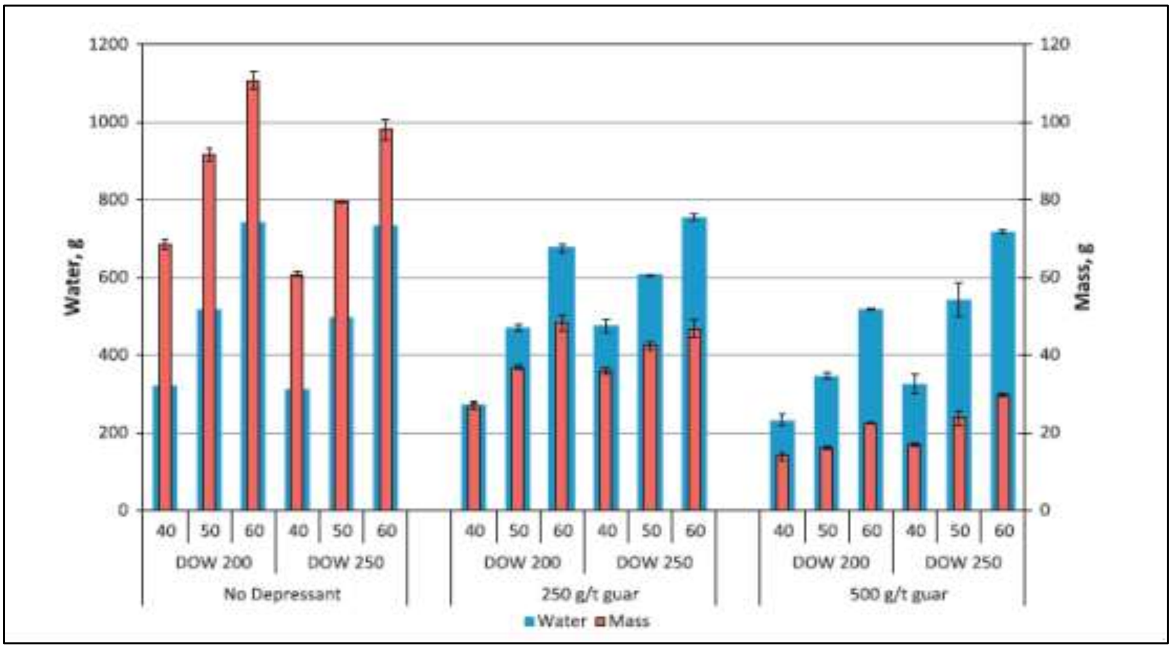


Figure 2.13 Effect of depressant dosage on water recovery and solid recovery (Wiese et al., 2012)

2.5 Factorial Design of Experiments

For an effective study of process parameter interaction, the factorial design approach is followed. In the factorial design approach the interdependency of process variable can be actively studied with targeted responses (Cochran and Cox, 1990 ; Araujo & Brereton, 1996). In the statistical design approach the experiments are conducted according to the design matrix. A full factorial design may also be called a fully crossed design. Such an experiment allows studying the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable.

For the vast majority of factorial experiments, each factor has only two levels. For example, with two factors each at two levels, a factorial experiment would have four treatment combinations in total, and is usually called a 2×2 factorial design.

2.6 Summary and Objective of Study

There has been much research carried out on the effects of the four different process parameters under discussion: air flow rate, froth depth, frother and depressant dosage (Ekmekci et al., 2003 Valenta, 2007). Each factor has an individual effect on PGM grade and recovery and on chromite grade and recovery. However, there is a need to gain a better understanding of the interactive effects of these factors. This research was aimed at investigating these interactive effects using a factorial design approach. In this way regions of good or poor operability may be determined which would maximise PGM grade and recovery, while minimising chromite grade and recovery.

2.7 Hypothesis to be tested

In the current investigation the following hypotheses were tested in the flotation of UG2 ore.

2.7.1 Froth Height

The mechanical entrainment of chromite can be reduced by increasing the froth height since this will increase the froth residence time, thus allowing for more drainage of chromite from froth to the pulp.

2.7.2 Superficial Air Velocity

The water recovery and solids recovery will increase with an increase in the superficial air velocity. The increase in the number of bubbles generated with increasing air flow rate will result in greater water recovery as well as solids recovery according to entrainment mechanisms.

2.7.3 Depressant Dosage

High depressant dosages will enhance the grade of PGMs and will decrease recovery of solids and water to the concentrate since all the naturally floatable gangue (NFGs) will be depressed. The reduced amount of solids in the froth phase may however destabilize the froth and result in lower solids and water recovery.

2.7.4 Frother Concentration

Increasing frother dosage will increase water recovery, decrease grade and increase recovery as a result of a decrease in bubble size causing more water to be transported into the froth by lamellae. The froth will become more stable and result in an increase in solids recovery and a decrease in grade.

2.7.5 Interactive Hypothesis

There exists a relationship between the operating parameters of frother dosage, depressant dosage, froth height and air flow rate such that it may be possible to maximize the PGM grades and recoveries while minimizing the chromite recoveries.

3 Experimental Details

3.1 Introduction

In Chapter 2 it was established that the effects of process parameters in the flotation process can have individual effects as well as interactive effects on flotation performance. In order to test the proposed hypotheses and to investigate the interactive effects that these process parameters have on flotation performance, a factorial design approach was followed for conducting the experimental work. Flotation tests were conducted using a laboratory-scale flotation column by using four factors at two levels. Twenty experiments were generated from the design matrix and the individual and interactive effects of the different responses were analysed statistically. This chapter describes the materials and experimental methods used in this study.

3.2 Materials

3.2.1 Ore Sample

A PGM bearing UG2 ore from Lonmin Platinum, South Africa was used in this study. A bulk ore sample, weighing approximately 500 kg was received at the Centre for Minerals Research (CMR), UCT. The run of mine (ROM) sample was crushed using first a Sturtevant jaw crusher and then a cone crusher supplied by Osborn MMD. The crushed sample was then blended and split into 1.3 kg sub samples using a rotary sample splitter supplied by Dickie and Stockler. The feed sample below 150 µm was, first split using a rotary splitter and then a micro-splitter to obtain a representative sample. The representative feed sample was sent to Lonmin platinum for chemical analysis. The chemical analysis of the ROM sample is shown in Table 3.1

Table 3.1 Chemical analysis of the ROM sample

PGM (g/ton)	Cr_2O_3 (%)	Cu (%)	Ni (%)
3.76	23.12	0.04	0.14

Characterization of the feed was conducted using QEMSCAN. The feed samples below 150 µm (+106, +75, +53, +25, +10, -10 µm) were, depending upon the quantity of the sample, split using a rotary splitter and then a micro-splitter to obtain a representative sample for each size fraction. After splitting in the micro-splitter, the samples were placed into plastic containers and sent for QEMSCAN analysis, the results of which are shown in section 4.1.

3.2.2 Water

All of the flotation tests were conducted using synthetic plant water, whereby distilled water was modified by the addition of various chemical salts to achieve a specific total dissolved solids content. The ions present in this synthetic plant water are shown in Table 3.2. The ionic concentrations were based on the typical values found at a selected PGM ore concentrator. Due to the nature of the gangue minerals in the ore it would be expected that these ions would be present in water being used at all concentrators of PGM ores, although total amounts could vary. The water was prepared in batches of 40 L (Appendix-I) which was sufficient for one column flotation test.

Table 3.2 Ions present in the synthetic plant water used in all flotation experiments

Ion	**Ca^{2+}**	**Mg^{2+}**	**Na^{+}**	**Cl^{-}**	**SO_4^{2-}**	**NO_3^{-}**	**NO_2^{-}**	**CO_3^{2-}**	**TDS**
Concentration (ppm)	**80**	**70**	**153**	**287**	**240**	**176**	**-**	**17**	**1023**

3.3 Flotation reagents

Initial test work was commenced using reagent suites described in the literature and from previous UCT experience in UG2 ore flotation. These included: collector, depressant and the frother. The type of reagents used and their characteristics are given in the subsections below.

3.3.1 Collector

In all flotation tests, sodium isobutyl xanthate (SIBX), with a purity of 90% and supplied by Senmin was used as a collector. The collector was supplied in powdered form and a 1% solution of the xanthate collector was prepared fresh for each test by hydrating it using distilled water. The collector was added at a dosage of 100 g/t.

3.3.2 Frother

The frother used in all the flotation tests was DOW 200 supplied by Betachem. It had a having specific gravity 0.973 and was supplied in liquid form. The concentration of frother varied for each test according to the design matrix.

3.3.3 Depressant

The depressant used in all the flotation tests was a guar gum, KU-9, supplied by GM Associates. The purity of the guar gum used in the testwork was determined to be 95% and it was supplied in powder form. The depressant solution was prepared fresh for each test by dissolving the guar gum in distilled water to achieve a concentration of 1% (w/w). The depressant dosage was varied according to the design matrix.

3.4 Equipment

Descriptions of the equipment used to conduct the flotation experiments are given below.

3.4.1 Mill

A Polaris stainless steel laboratory rod mill as shown in Figure 3.1 was used for milling the ore. The mill had a diameter of 300 mm and a length of 298 mm. The mill charge consisted of 22 stainless steel rods each with a diameter of 25 mm. The grinding of the ore was conducted by milling a 3.9 kg ore sample together with 1000 ml synthetic plant water at a mill speed of 75.3 Hz. No reagents were added to the mill.

Figure 3.1 Picture of the rod mill

3.4.2 Flotation Column

A laboratory column flotation cell adapted from Xu et al. (1996) was used for the study. The locally fabricated flotation column had an internal diameter of 4.6 cm and a height of 200 cm and was made of Plexiglas to enable detection of the pulp froth interface during the flotation process. The column was mounted on a wooden frame for ease of operation and to provide stability during experiments. A launder was located at the top of the column for the collection of flotation concentrates. The froth level was controlled by a level controller based on a PID control mechanism. The controller had a pressure transducer located 80 cm from the top of the column. It controlled the flow rate of the tailing pump to achieve the desired froth height. A mixture of slurry and air were co-fed near the bottom of the column via an stainless steel sparger which generated small bubbles by means of a shearing action. The recirculation pump flow rate was placed at the same level of the feed flow rate to create sufficient turbulence in order to aid collision between the particles and bubbles. The sparger consisted of three feed ports for the air, feed and recirculated slurry respectively. Synthetic air was used as the flotation gas and was controlled using a needle valve. The air flow rate was measured with a rotameter which was regularly calibrated using a soap bubble meter. The recirculation pump was placed before the external sparger to create turbulence, sufficient for bubble-particle collision. A schematic diagram of the column is shown in Figure 3.2 (Alvarez-Silva et al., 2012). A photograph of the flotation column is shown in Figure 3.3.

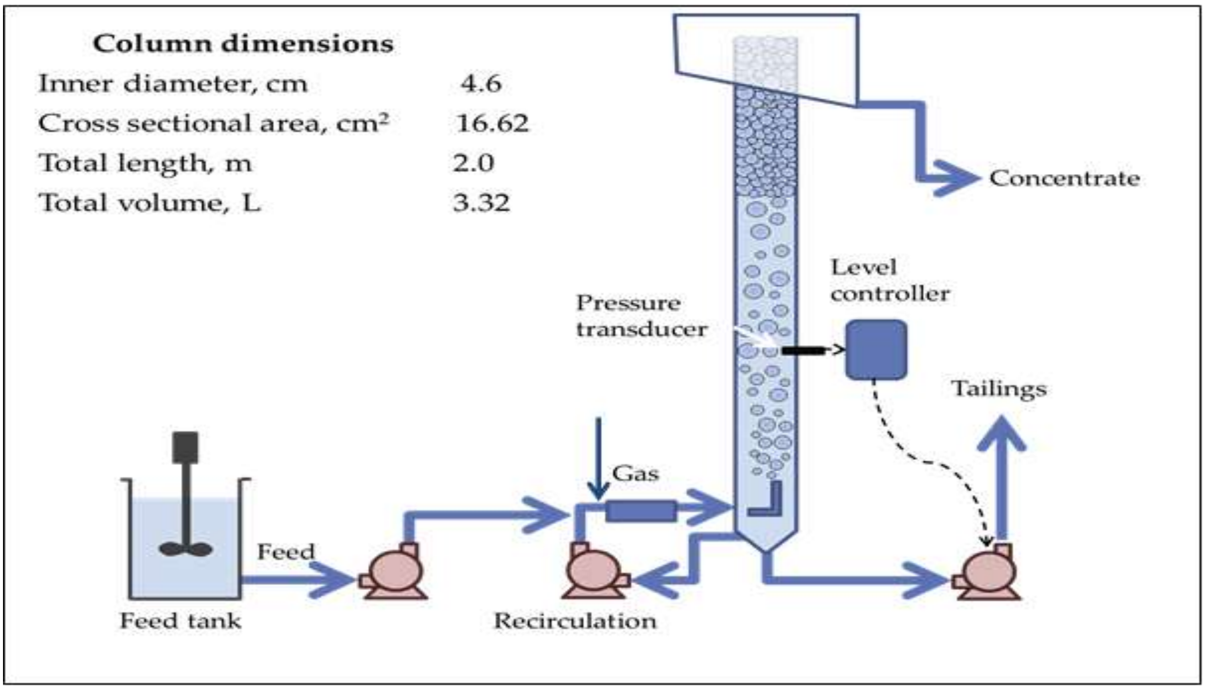


Figure 3.2 Schematic diagram of the column flotation rig

Figure 3.3 Photograph of the column flotation rig

3.4.3 Pumps

Three pumps were used to operate the column flotation cell. These were a feed pump, a tailing pump and a recycle pump. The pumps were Watson Marlow 600 series pumps. The feed and recycle pump flow rates were controlled by a variable speed drive while the tailing pump was controlled by the PID controller.

3.4.4 Feed Tank and Agitator

In order to create a slurry of uniform density and to ensure sufficient mixing, a feed tank was used to make up the feed slurry. The feed and water were mixed in a 40 litre HDPE (High density poly ethylene) tank using an agitator with a fixed speed of 1000 rpm.

3.4.5 Air Supply

Synthetic air was used as the flotation gas in the experiments. The air was supplied to the rotameter via a needle valve at a fixed pressure of 2 bar.

3.5 Experimental Procedures

Certain procedures were followed for sample preparation as well as for the smooth operation of the equipment. These procedures are given below.

3.5.1 Milling

In order to prepare sufficient flotation feed to run one experiment in the flotation column, 3 x 1.3 kg portions of ore i.e. 3.9 kg were milled using synthetic plant water at 66 % solids in a stainless steel rod mill to achieve a grind of 60% passing 75 µm. In order to determine the time required to achieve this grind, a milling curve was established by grinding the ore for different times and determining the amount passing 75 µm. The cumulative percent passing 75 µm as a function of grinding time is shown in Figure 3.4 demonstrating that a grind of 60% passing 75 µm was obtained after milling the ore for 27 minutes and 40 seconds. After grinding the ore at the optimum grinding time, the size distribution of the particles was determined using a Malvern particle size analyser. The result of particle size analysis are shown in section 4.1.

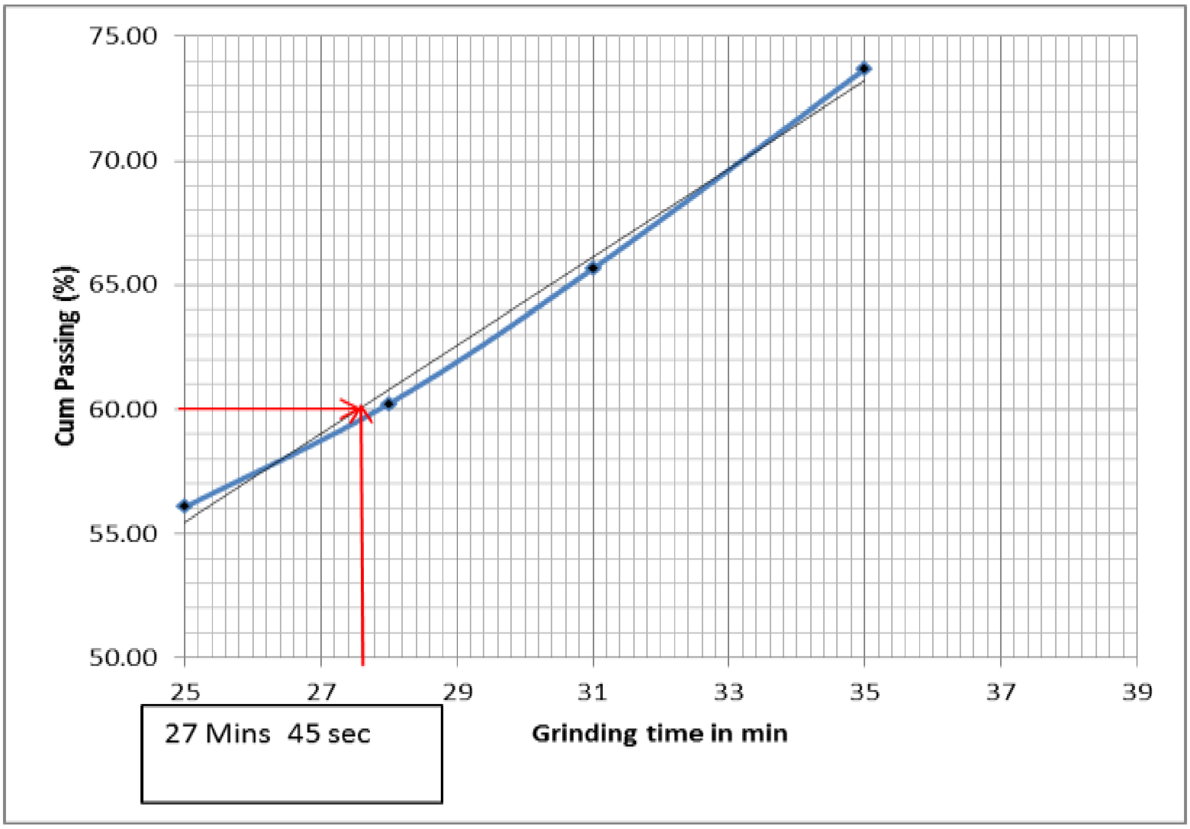


Figure 3.4 Milling curve for optimum grinding time

3.5.2 Commissioning of column

The commissioning of the flotation column was done in the series of steps as given below.

3.5.2.1 Calibration of Pumps and Air flow meter

The calibration of the flow rates of the feed and recycle pump was done by measuring the flow rate of water at different frequencies. The feed and recycle pumps were operated by variable speed drives connected to them. The frequencies were noted with different flow rates of water and the relationship with flow rate was established.

The air flow meter (rotameter) was calibrated using a soap bubble meter as shown in Figure 3.5. The air flow meter was connected to a vacuum pump and the air was sucked by the vacuum pump at a fixed pressure. The other end of the rotameter was connected to the soap bubble meter. The soap bubble meter consisted of a graduated cylinder with three open points One end was dipped into the soap solution while the other end was connected to the rotameter and the third port was used for air control.

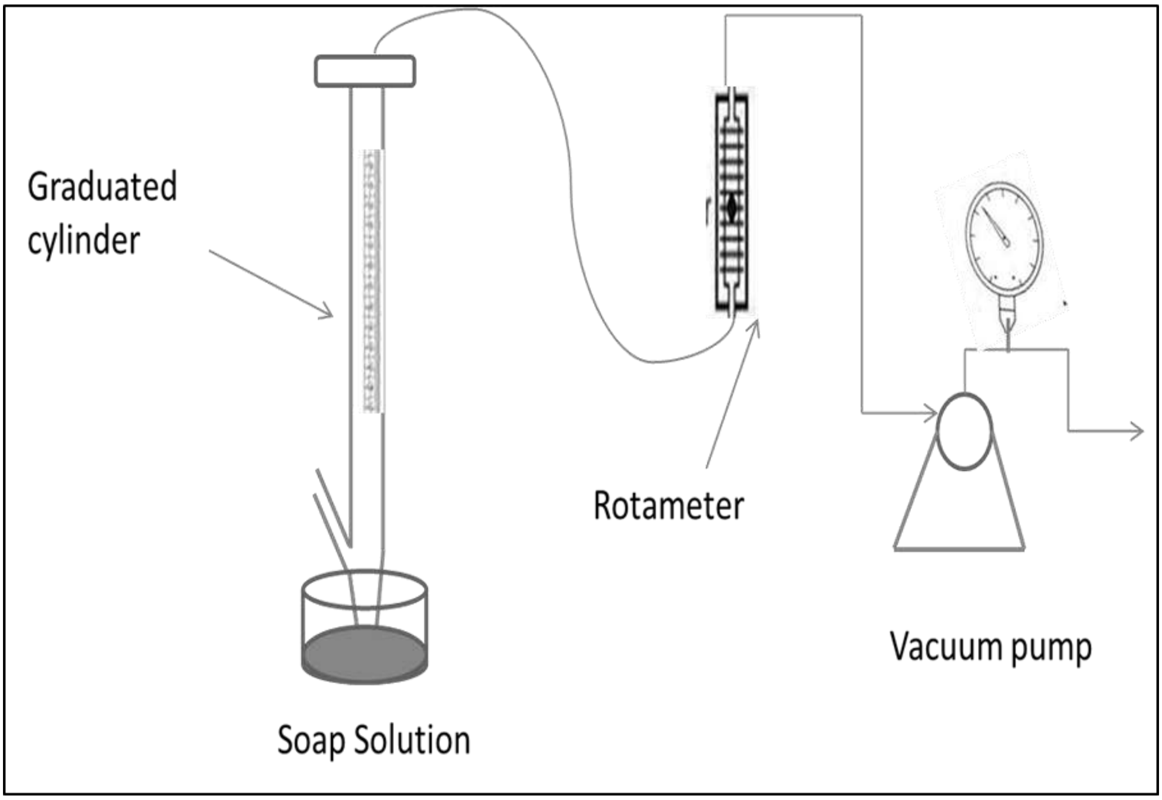


Figure 3.5 Schematic showing calibration of rotameter using a soap bubble meter

The air flow meter was set and air was allowed to pass through it via the graduated cylinder. The time period taken for the air bubble to travel from one end of the cylinder to the other was noted and the flow rate was calculated and matched with the fixed flow rate of the rotameter. In this test work it was found that at 2 bar pressure the actual flow rates and measured flow rates were equal for the rotameter.

3.5.2.2 Determination of the Operational Parameters: pulp density, froth height and air flow rate

In order to establish an optimum pulp density for the operation of the column, experiments were conducted at different solids concentrations ranging from 15 to 30%. At almost all solids concentrations evaluated the pulp-froth interface was not visible as shown in Figure 3.6. Therefore, there was no clear demarcation between the pulp and froth phases. The pulp-froth interface was, however, apparent at a solids concentration of 16%, which was selected for use in all future experiments.

Figure 3.6 (a) No pulp-froth interface apparent (18% solids) (b) Pulp-froth interface is visible (16 % solids)

Similarly, for better interface visibility the minimum froth height was determined as 18 cm and the maximum air flow rate as 1.5 l/min.

3.5.3 Standard Column Flotation Procedure

The ground feed slurry was mixed with synthetic plant water to achieve a uniform solids concentration of 16%. The pulp was mixed 15 minutes prior to reagent addition in order to ensure complete suspension of solids. The collector was added first, followed by the depressant and finally the frother. Each reagent was added 2 minutes after the other to allow sufficient conditioning time. Finally, the slurry was kept in suspension for 15 minutes before being fed to the column. The conditioned slurry was fed to the column at a constant flow rate of 1 l/min. The column was operated in closed circuit before steady state was achieved. After steady state was reached, the column was operated in open circuit for 7 to 9 minutes (i.e. 2 to 3 mean residence times). The next step involved the collection of samples from the feed tank simultaneously with sample collection from the tailings and concentrate streams for precisely two minutes each. Five consecutive samples were collected during each test. A test was considered valid when the overall solids mass balance for the entire run was within 10 % (i.e. concentrate plus tailings vs feed).

3.6 Design of Experiments

This study made use of a laboratory scale column flotation cell operated in a continuous steady state mode in open circuit to evaluate the effect of frother concentration, depressant dosage, froth height and superficial gas velocity on the flotation performance of UG2 ore. For the effective study of process parameters the experiments were carried out using a factorial design approach.

Table 3.3 Parameters employed in flotation system

Constant parameters	**Variable parameters**
Collector dosage, Feed flow rate	Frother dosage, Depressant dosage, Superficial air velocity, Froth height.

Table 3.4 Factors and levels for factorial design

Parameters	Froth height (cm)	Superficial air velocity (cm/s)	Depressant (Guar gum) (g/t)	Frother dosage (DOW 200) (ppm)
Levels (Min.)	18	0.5	100	10
Levels (Max.)	30	1.5	300	30

Table 3.5 Design matrix for factorial design of experiments

Test Number	Froth Height (cm)	Superficial air velocity (cm/s)	Depressant Dosage (g/t)	Frother Dosage (ppm)
1	18	1.5	300	10
2	24	1	200	20
3	24	1	200	20
4	30	1.5	300	10
5	18	1.5	100	30
6	18	1.5	100	10
7	30	0.5	100	10
8	18	0.5	300	30
9	30	0.5	100	30
10	30	1.5	100	30
11	24	1	200	20
12	18	1.5	300	30
13	30	1.5	100	10
14	18	0.5	100	30
15	30	1.5	300	30
16	24	1	200	20
17	18	0.5	300	10
18	18	0.5	100	10
19	30	0.5	300	30
20	30	0.5	300	10

The use of factorial design allows for the simultaneous study of the effect of several dependent factors on a process, as well as varying the levels of the factors instantaneously. This is preferable to varying one parameter at a time for the study of factor interactions and a system such as this has a distinct advantage over standard laboratory batch flotation cells since it permits the study of the influence of the froth phase on the flotation process using significant froth heights compared to what is possible in a standard batch flotation cell. Moreover, using a continuous process operated at steady state is much more relevant to the real process than the more complicated non-steady state batch system.

The constant and variable factors employed in the flotation system used in this study are given in Table 3.3. For studying the interactive effects of the process variables, a statistical design approach was followed. The experiments were carried out by using four important factors at two levels. The factors and levels are given in Table 3.4.

Twenty different sets of experimental conditions were generated using a full factorial design matrix. Of the 20 experiments, 4 were at the base level and the remaining 16 experiments were the actual tests conducted to assess the interactive influence of flotation process parameters. The experimental error was determined from the base level study, and was found to be in +/2% (the details are given in Chapter 4). The design matrix of the experiments is given in Table 3.5.

3.7 Analysis of Performance

The results of the factorial design of experiments were analysed by means of ANOVA using a statistical design software package (Design Expert-8). Design Expert uses the method of least squares to fit a linear model to the data. An output to the data is an analysis of variance (ANOVA) table where the main effects are tested for significance by the *F*-test. Regression equation were developed for the effect of the factors on the responses. The confidence level for the models was set at 95%. Anything outside this boundary was discarded from the model. The factors in the regression equation are coded according to equation 3.1 (Yi et al., 2010):

$$Coded\ Value = \frac{Original\ Value - Midpoint\ Value}{Interval\ Value} \qquad (3.1)$$

This equation can be explained by an example, where at low level the original value of froth height is 18 cm and the midpoint value is 24 cm and the interval value is 6. If we put the values in equation 3.1 it will yield a value of -1 which is our coded low level. Similar kind of expression valid at high levels.

4 Results

This chapter describes the results obtained from flotation tests conducted using the continuous column flotation cell to investigate the individual effect of process parameters and their interactions on the responses of solids recovery, water recovery, chrome recovery and grade and PGM recovery and grade. It begins with Section 4.1 and the characterization of feed and description of particle size in the flotation feed. Section 4.2 illustrates the results of the experimental reproducibility at base level conditions. Section 4.3 covers the results of factorial design of experiments with a preliminary set of conditions. From the results of a preliminary set of conditions in section 4.3 it was observed that the solid and water recoveries were low as a result of low frother concentration. To overcome the problem, the frother concentration was increased and the results of these experiments are shown in section 4.4.

4.1 Characterization of Feed Sample

The particle size analysis of the milled feed sample was done using a Malvern particle size analyser and is shown in Figure 4.1.The results obtained, indicated that 60% of the particles were less than 75 µm in size and 80% of the particles were less than 120 µm in size. Only 10% of the particles were below an ultrafine size range of 10 µm. Around 70% of the particles were between 10 to 100 µm .

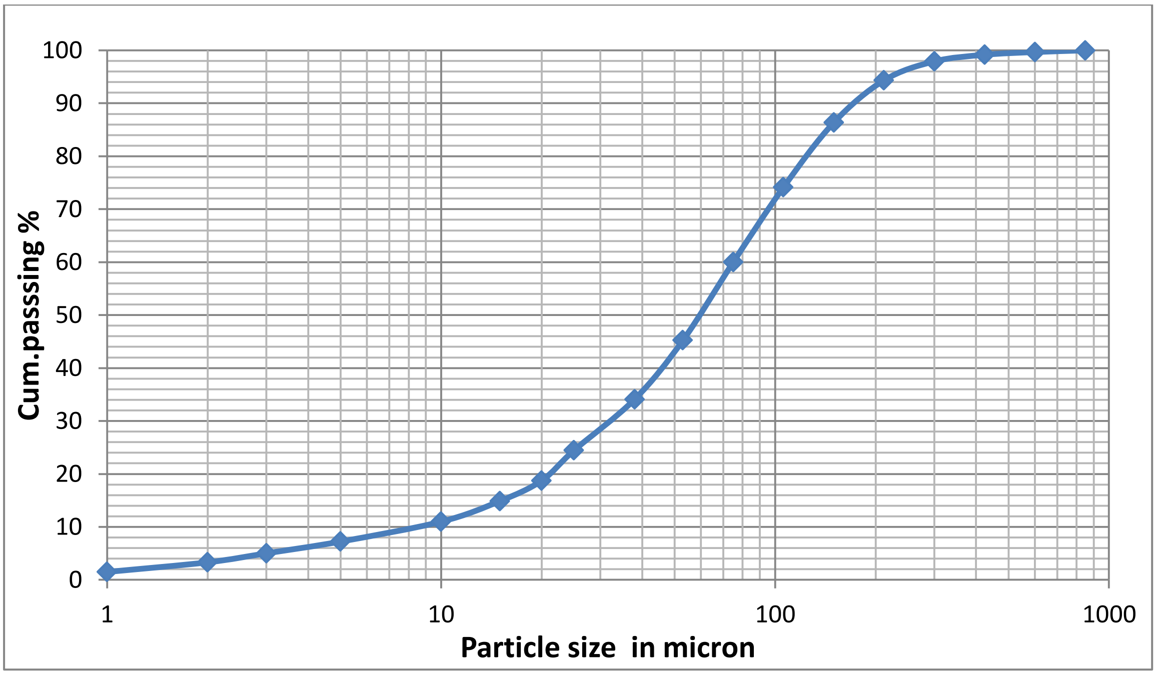


Figure 4.1 Particle size analysis of feed sample

A bulk modal analysis of the feed sample of the ore was conducted using QEMSCAN at UCT. The system uses energy dispersive X-ray spectra and back scattered electron image information to identify minerals . The overall mineral presence in the feed sample is shown in Figure 4.2 and the distribution of minerals in each size fraction in the ore is shown in Table 4.1. The bulk mineralogy shows that the feed had a base metal sulphide content of about 0.16%. It can be observed that chromite was the dominant mineral present in the feed sample. Other gangue minerals like orthopyroxene and plagioclasewere also present in significant amounts. The naturally floatable gangue mineral, talc, was also present in noteworthy amounts (2.07%).

From the modal analysis it can be concluded that much of the base metal sulphides were present in the ultrafine fraction (-10 µm). The chromite content was relatively constant in all the size fractions. The natural floatable gangue mineral, talc, was also present in significant amounts in the -25 µm fraction.

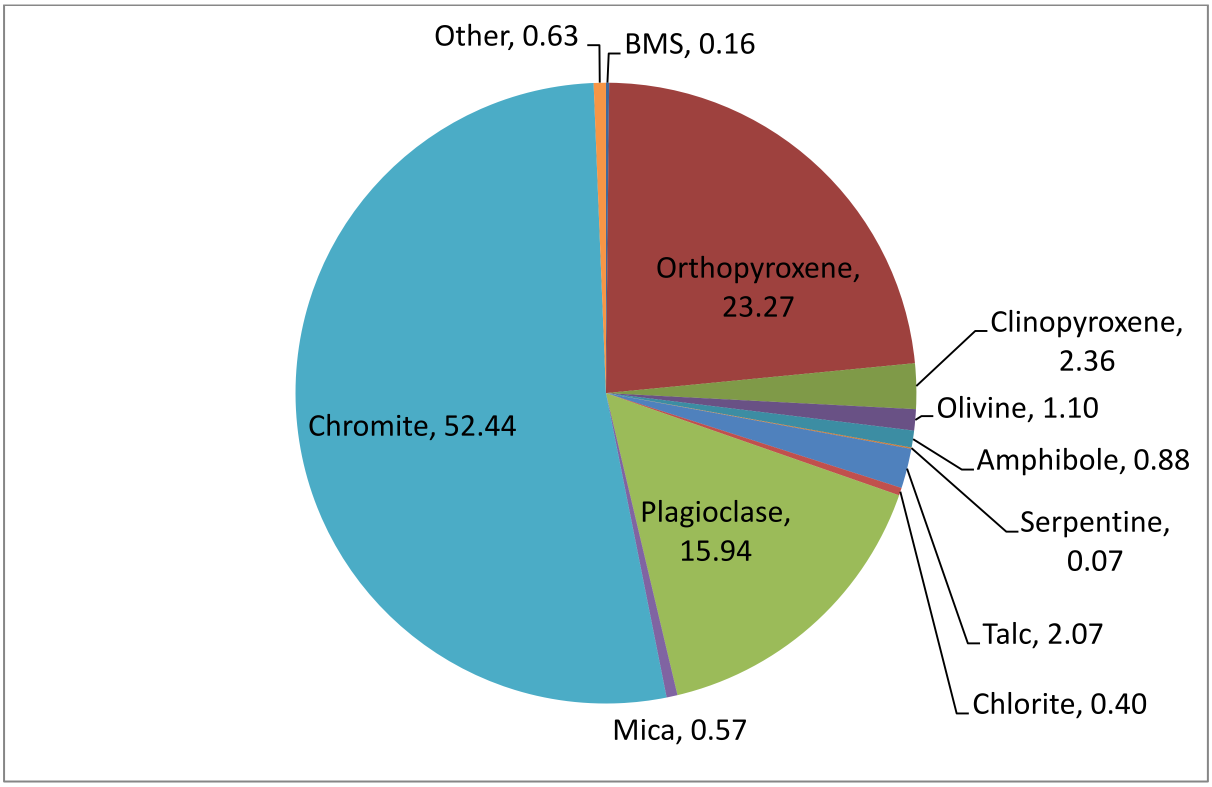


Figure 4.2 Distribution of minerals in the feed

Table 4.1 Distribution of minerals in each size fraction of feed

Minerals	Size Fractions						Combined
	-1000/+106	-106/+75	-75/+53	-53/+25	-25/+10	-10	
BMS	0.02	0.03	0.07	0.31	0.30	0.68	0.16
Orthopyroxene	34.30	24.48	20.72	22.43	19.71	16.46	23.27
Clinopyroxene	2.67	2.10	2.49	2.57	2.50	1.64	2.36
Olivine	1.28	1.13	1.14	1.34	0.68	0.53	1.10
Amphibole	0.59	0.43	0.42	0.53	1.73	4.81	0.88
Serpentine	0.06	0.06	0.01	0.05	0.12	0.26	0.07
Talc	1.68	1.84	0.59	1.07	4.42	8.17	2.07
Chlorite	0.15	0.08	0.15	0.12	0.65	3.80	0.40
Plagioclase	10.35	14.96	15.57	17.62	19.17	20.71	15.94
Mica	0.30	0.32	0.40	0.73	1.15	1.19	0.57
Chromite	48.31	54.20	57.90	52.56	48.68	39.38	52.44
Other	0.28	0.37	0.53	0.66	0.88	2.37	0.63
Total	100	100	100	100	100	100	100

4.2 Reproducibility Tests

As discussed in Chapter 3, the experiments were done according to a factorial design matrix. This included four centre points to check for curvature and reproducibility. Five replicate flotation tests were conducted in order to determine the standard error associated with a particular result. The standard error, which was obtained by dividing the sample standard deviation by the square root of the number of repeats, was used as a guide in order to evaluate the reproducibility of the data. The results of base level tests are given in Figure 4.3 for the responses of solid recovery water recovery.

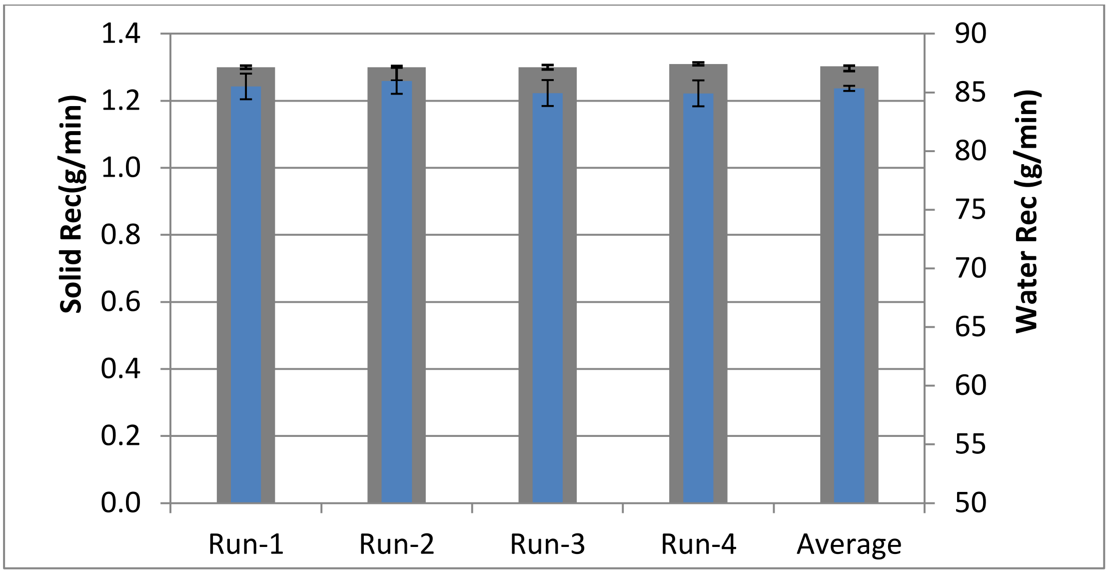


Figure 4.3 Solid recovery and water recovery at base level conditions

The experimental conditions at centre point were as follows.

Froth height = 24 cm, Superficial air velocity = 1 cm/sec, Depressant dosage = 200 g/ton and Frother concentration = 20 ppm

From the Figure 4.3, it can be observed that in the base level conditions the solid recovery was 1.3 g/min and the water recovery was approximately 86 g/min with a standard error of +/- 2%.

4.3 Results of Preliminary Set of Conditions

Four important factors, presented in Section 3.6, were studied for the initial factorial design experiments. The results of the different responses (solid and water recoveries, chrome recovery and grade, PGM recovery and grade) are discussed below.

4.3.1 Response of Water recovery and Solids recovery

The solids and water recoveries under different sets of conditions are shown in Figure 4.4. From Figure 4.4 it can be seen that solid and water recoveries were far lower at 10 ppm frother concentration compared to 30 ppm frother concentration. The frother concentration played a major role in water recovery and solid recovery in comparison to other factors. At 10 ppm frother concentration, it is difficult to assess the effects of the other parameters on the solids and water recoveries since the recoveries were so low. However, it can be observed that froth height played a role, in that higher froth heights resulted in reduced solids and water recoveries. In addition, solids and water recoveries were generally lower at higher depressant dosages. There was no clear effect due to air flow rate. At 30 ppm frother concentration, the other factors had a more pronounced effect on solids recovery and water recovery. The froth height and superficial air velocity showed the greatest effect on solids recovery and water recovery. The solids recovery and water recovery decreased with an increase in froth height. Similarly, in the case of superficial air velocity, the solids recovery and water recovery increased with an increase in superficial air velocity. In the case of depressant dosage there was no consistency with regards to the solids and water recoveries. It has been shown that depressant dosage did not have a very strong influence on solid and water recovery under these conditions.

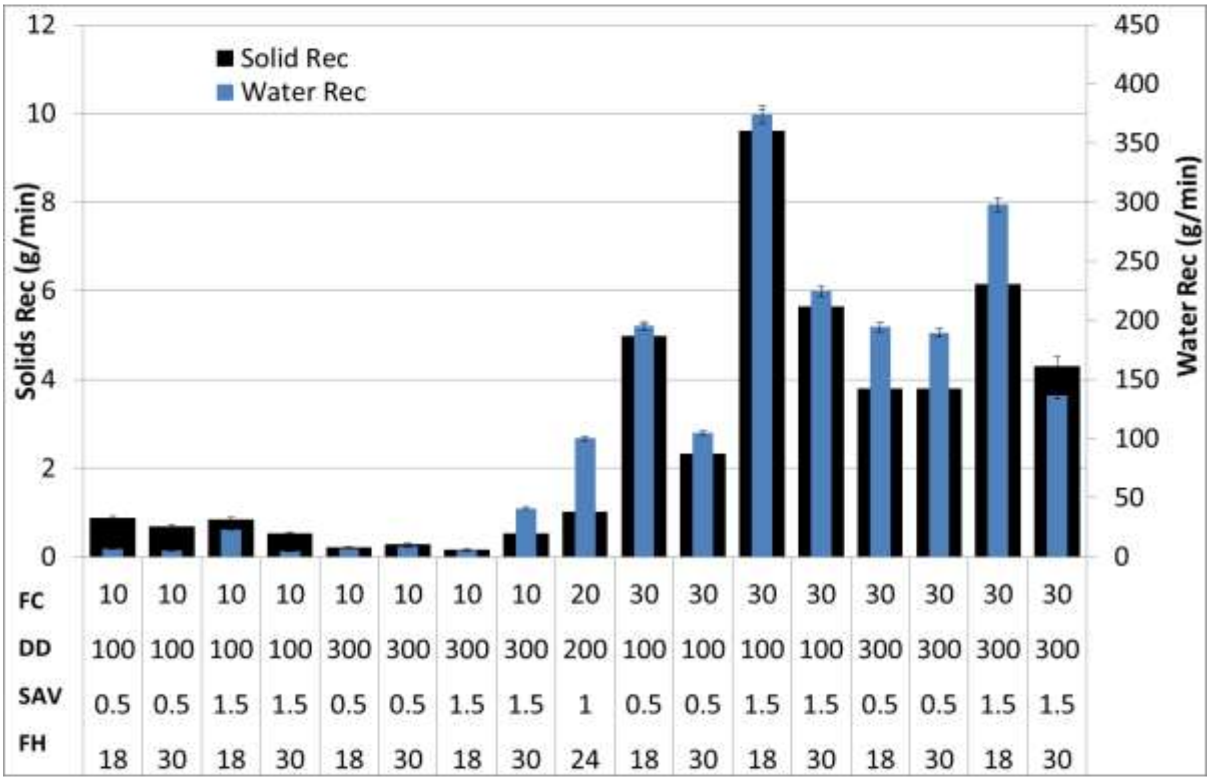


Figure 4.4 Solids recovery and water recovery from tests conducted at preliminary conditions

Where FC= Frother concentration, DD= Depressant dosage, SAV= Superficial velocity, FH=Froth height

4.3.2 Response of Chrome recovery and Chrome grade

From the Figure 4.5 it can be seen that the chrome recovery and chrome grade follow the trend of water recovery and solids recovery in that the chrome recovery and grade were lowest in the case of the lower frother concentration. Thus, at lower frother concentrations, the chrome grade increased with an increase in depressant dosage, even at high froth height. The superficial air velocity had a significant effect at low frother dosage. This suggests that frother concentration had a pronounced effect on chrome recovery. In the case of higher frother concentration the chrome recovery and chrome grade were high in comparison to conditions of lower concentration of frother. At higher concentrations of frother the superficial air velocity and froth height played a governing role in chrome recovery and chrome grade. In general, the chrome recovery and grade decreased with an increase in froth height while keeping other parameters constant at higher frother concentration. Similarly, there was a general increase in chrome recovery and grade with an increase in superficial air velocity with higher frother concentration. The chrome recovery and chrome grade increased slightly with increasing dosage of depressant at lower froth height. At high froth height with constant superficial velocity and frother concentration it can be observed that there was also a slight decrease in chrome recovery and chrome grade. Moreover, the results suggest that depressant dosage had a negligible effect on chrome recovery under the conditions evaluated.

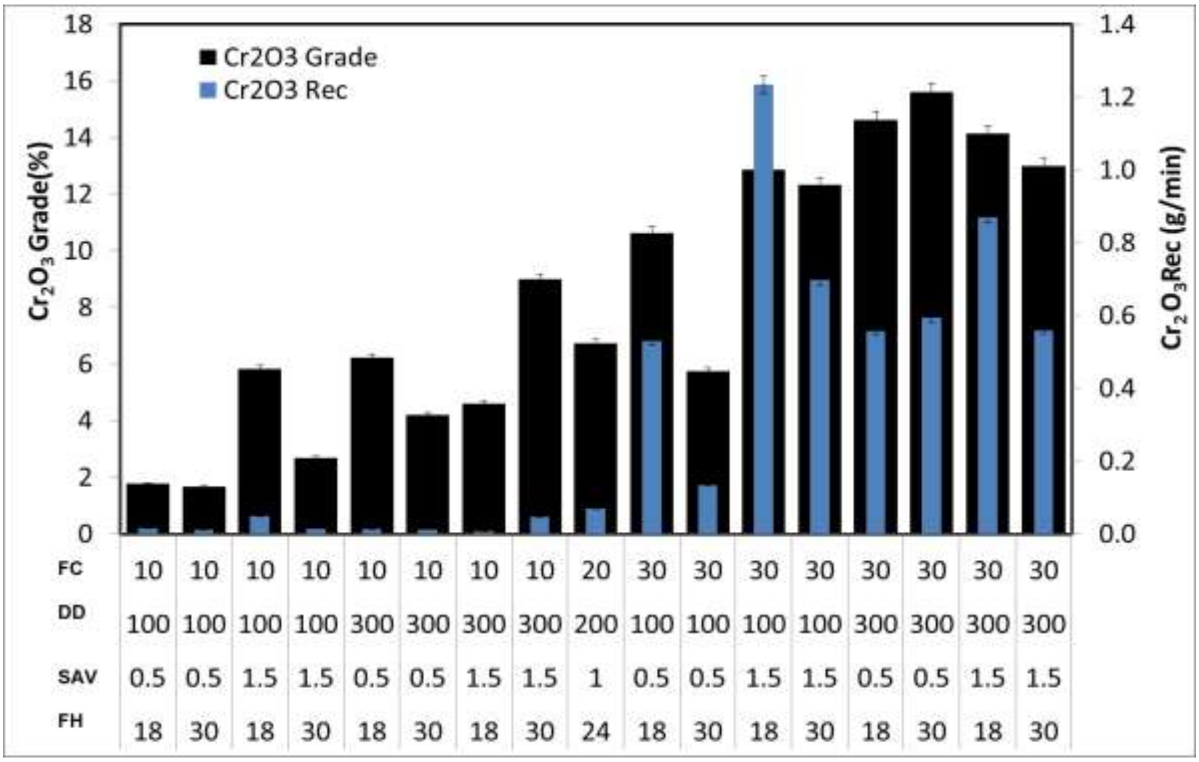


Figure 4.5 Chrome recovery and Chrome grade from tests conducted at preliminary conditions

4.3.3 Response of PGM recovery and PGM grade

The results obtained for PGM recovery and grade are shown in Figure 4.6. Frother concentration played a major role in PGM grade when compared to other factors. Frother concentration did not have as large an impact on the PGM recovery as in the case of solids, water and chrome recovery. The average PGM grade at 10 ppm frother concentration was 1800 g/t while the average grade at 30 ppm was less than 200 g/t . At higher frother concentration, however, the PGM grade decreased drastically from 1800 g/t to 200 g/t. The other factors evaluated i.e. froth height, superficial air velocity and depressant dosage had little effect on PGM recovery and grade at 10 ppm frother concentration. There was an increase in PGM grade with an increase in froth height. The PGM recovery did not significantly change with changes in the process parameters.

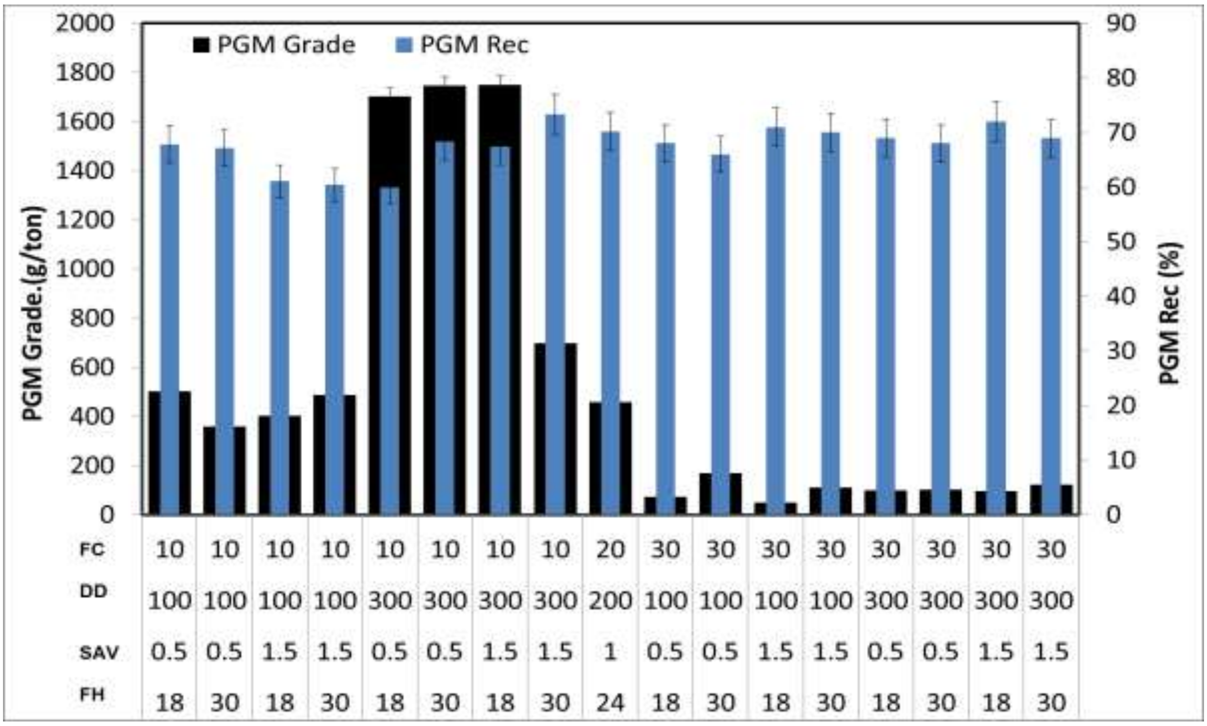


Figure 4.6 PGM recovery and PGM grade from tests conducted at preliminary conditions

After analysing these results, it was concluded that the lower concentration of frother (10 ppm) was not suitable for studying the interactive effect of factors by factorial design. Thus, the minimum frother concentration was increased from 10 ppm to 20 ppm, and the experiments were repeated. The results of the factorial design of these experiments are given in section 4.4.

4.4 Results of Factorial Design at Established Conditions

The second set of factorial design experiments were carried out with the same parameters. The minimum frother dosage was increased to 20 ppm. Other parameters were the same as in the first set of experiments. The results of solids recovery and water recovery are given in Figure 4.7. It can be observed that there is much variation on solids and water recovery within each frother concentration, indicating that the frother concentration did not have the overriding effect as in the previous set of experiments. For example, at 20 ppm frother dosage, it can be seen that froth height had a major effect on solids and water recovery, in that there were substantially less solids and water recovered at the high froth height than at the low froth height. This is also evident for the 30 ppm frother concentration. It is also clear from Figure 4.7 that the superficial air velocity had a large effect on the solids recovery and water recovery, with solids and water increasing with increasing air flow rate. Depressant dosage appears not to have had a large effect on the solids and water recovery, since there is not a large difference between recoveries at different depressant dosages. The solids recovery and water recovery values were found to be maximum (9 g/min of solids and 370 g/min of water) at high frother concentration, high superficial air velocity, low froth height and low depressant dosage.

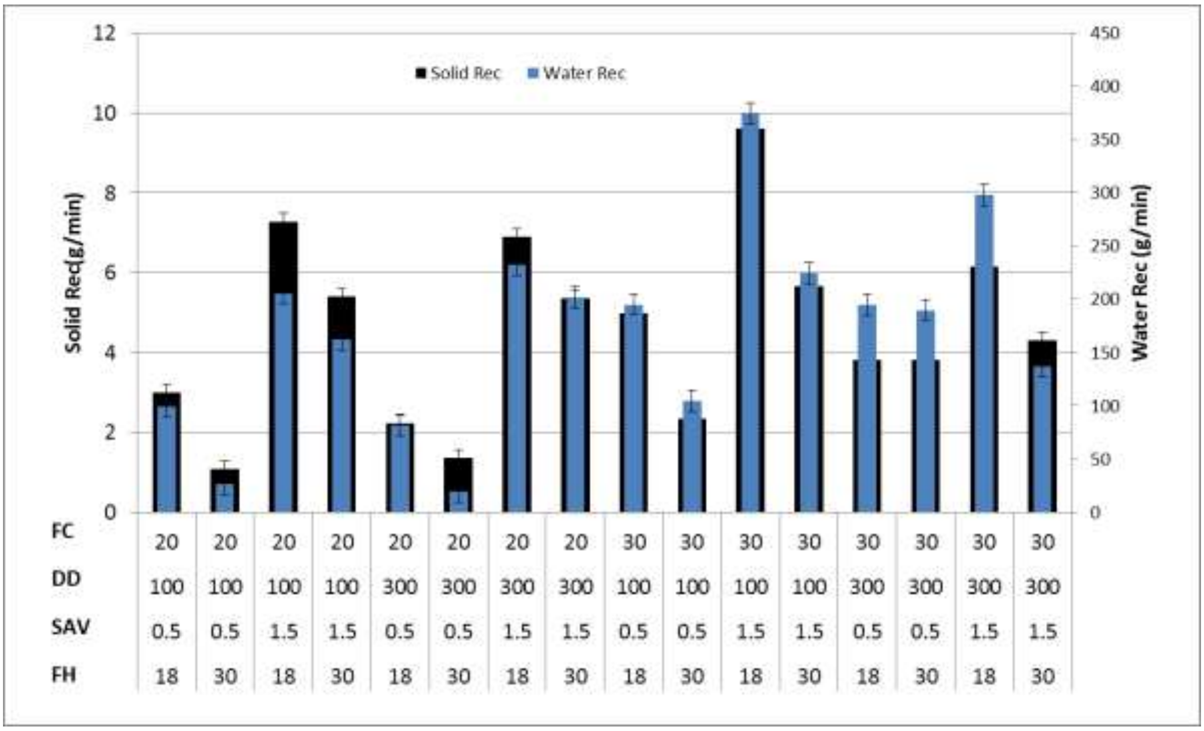


Figure 4.7 Solids recovery and water recovery from tests conducted at factorial conditions

The results of chrome recovery and grade for the various experimental conditions are given in Figure 4.8. It can be observed that the froth height and superficial air velocity had a major effect on chrome recovery. Chrome grade and recovery decreased with an increase in froth height and a decrease in superficial air velocity. The depressant dosage had varying effects on chrome recovery and grade in concentrate. In many instances there was an increase in grade and recovery with increasing depressant dosage, while in some there was an increase in grade, but a decrease in recovery. High frother concentration, high superficial air velocity, low froth height and either high or low depressant dosage caused the chrome recovery to reach a maximum (~1.2 g/min). Low chrome grade (less than 4%) was observed with low frother concentration, low depressant dosage, high froth height and low superficial air velocity.

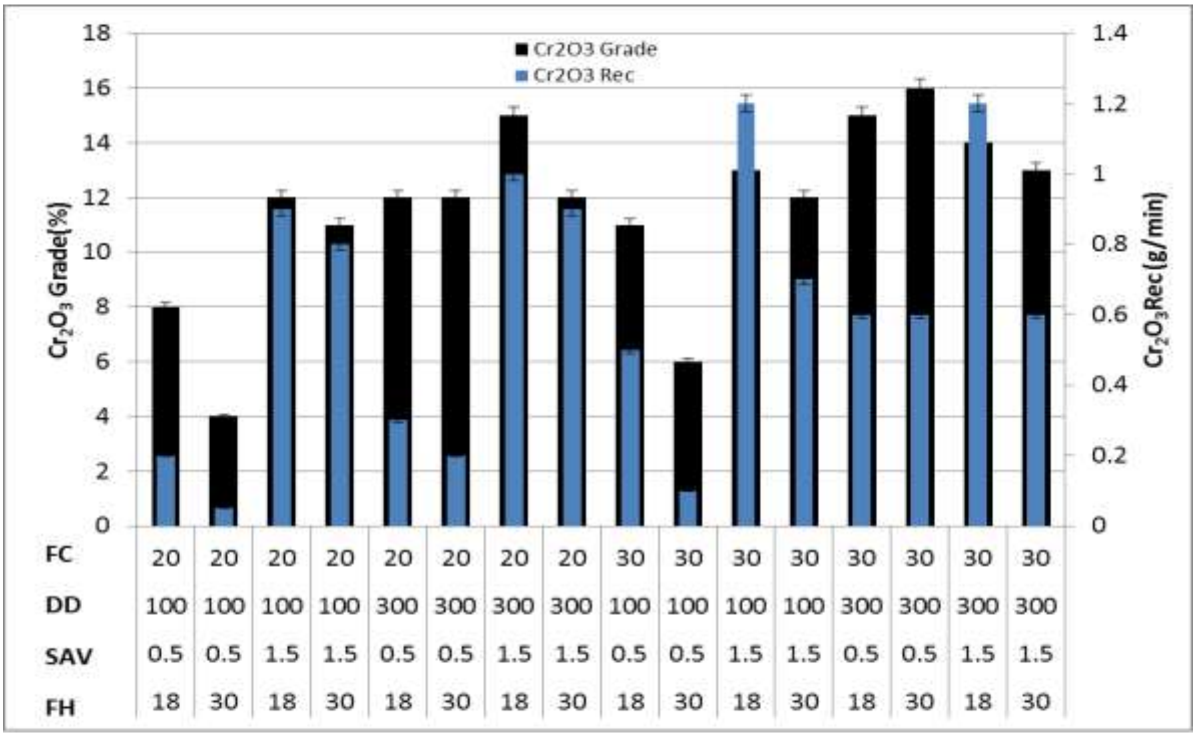


Figure 4.8 Chromite recovery and chromite grade from tests conducted at factorial conditions

The chrome recovery was plotted as a function of water recovery as shown in Figure 4.9 As expected the chrome recovery was linearly proportional to the water recovery. This suggests that the chrome was recovered purely by entrainment, with 0.0036 g of Cr_2O_3 being recovered for every gram of water recovered.

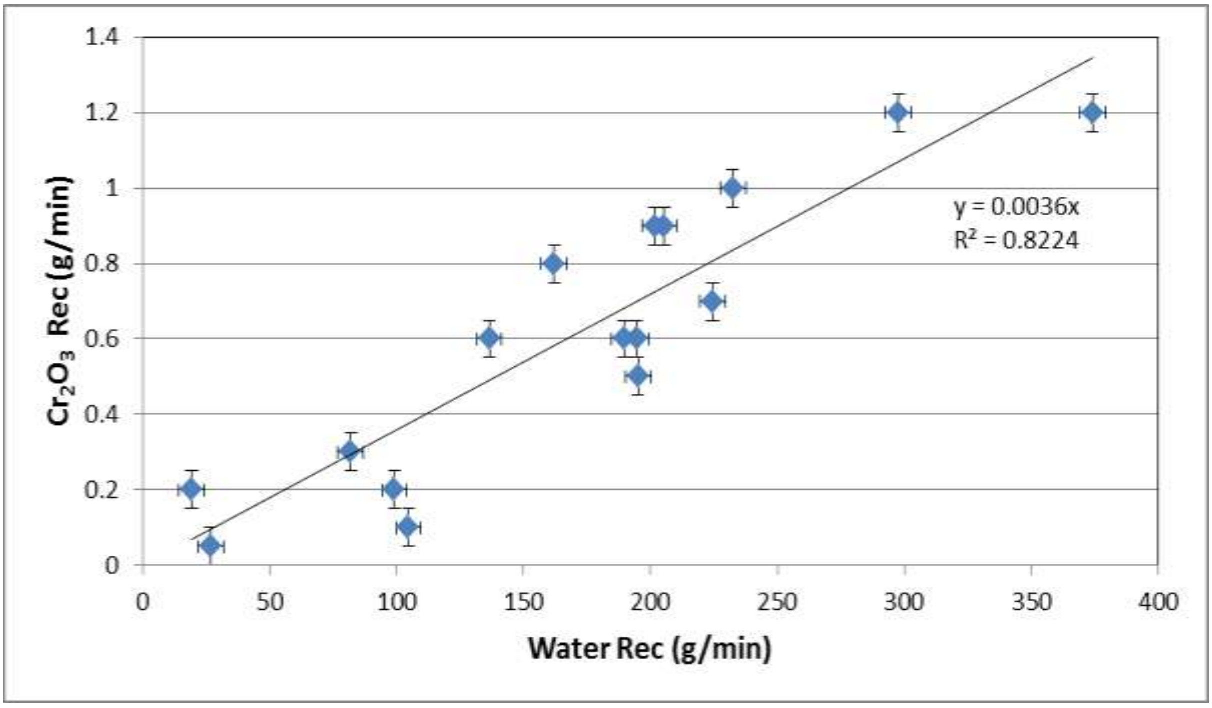
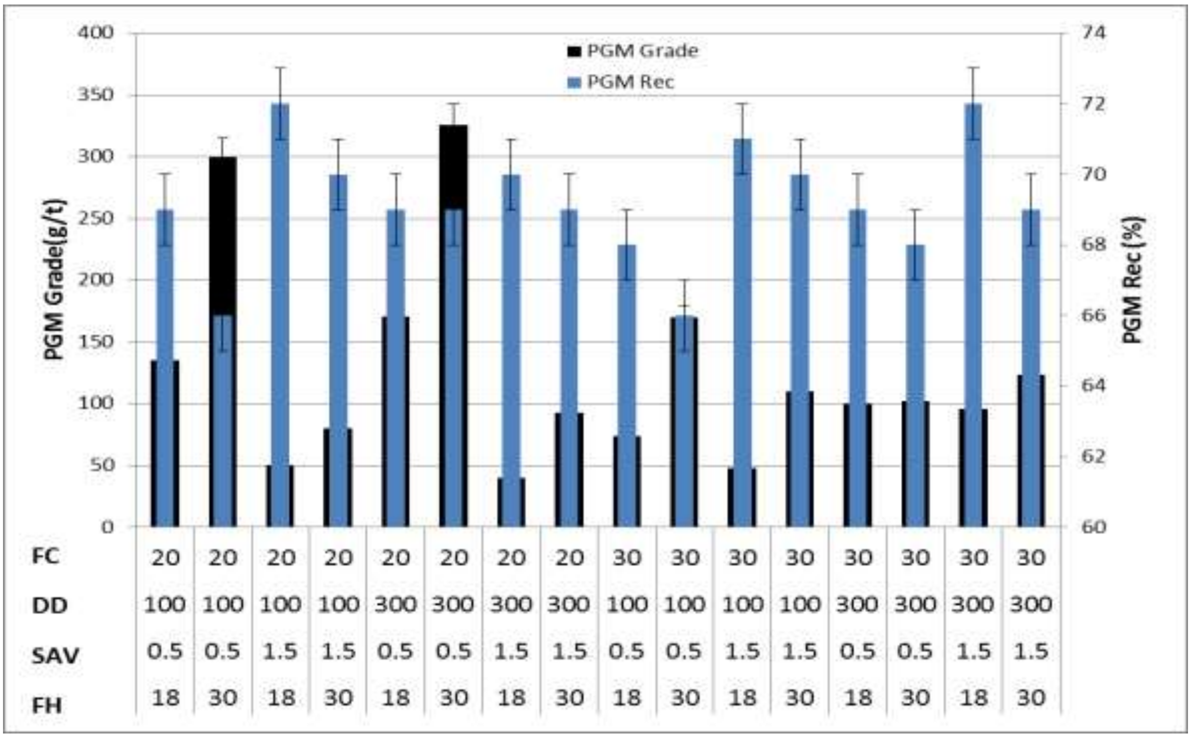


Figure 4.9 Chromite recovery as a function of Water recovery from tests conducted at factorial conditions

Figure 4.10 shows the PGM grade and recovery at each of the experimental conditions evaluated. It can be observed that the froth height and superficial air velocity had major effects on both the recovery and grade of PGM's in the concentrates. An increase in froth height was, in most cases, associated with a decrease in PGM recovery and an increase in grade. Conversely, an increase in air flow rate was associated with an increase in PGM recovery and a decrease in grade. This highlights that there is a trade-off between grade and recovery. The highest recoveries were noted at high air flow rates and low froth heights, with the highest grades being at low frother concentrations, high depressant dosage, low air flow rate and low froth height.



FC	20	20	20	20	20	20	20	20	30	30	30	30	30	30	30	30
DD	100	100	100	100	300	300	300	300	100	100	100	100	300	300	300	300
SAV	0.5	0.5	1.5	1.5	0.5	0.5	1.5	1.5	0.5	0.5	1.5	1.5	0.5	0.5	1.5	1.5
FH	18	30	18	30	18	30	18	30	18	30	18	30	18	30	18	30

Figure 4.10 PGM recovery and PGM grade from tests conducted at factorial conditions

4.5 Major Effects and Interactions

The effects of the four factors were studied for various responses. A regression equation was developed and analysed by ANOVA. The responses which were studied are given below.

1. Solids Recovery
2. Water Recovery
3. Chromite Recovery
4. Chromite Grade
5. PGM Recovery
6. PGM Grade

The responses and their significance are shown in Table 4.2. It can be observed that, froth height and superficial air velocity contributed expressively in most of the responses at 95% confidence levels. The detailed results are given in subsequent sections.

Table 4.2 Effect of factors and their contribution on different responses

Response	Term	P value Prob>F	Effect on response	% Contribution
Solid Recovery	Froth height	0.0044	Negative	17
	Superficial Air Velocity	0.0001	Positive	62
	Frother Concentration	0.0801	Positive	5
Water Recovery	Froth height	0.0021	Negative	18
	Superficial Air Velocity	0.0001	Positive	41
	Frother Concentration	0.0010	Positive	23
	Superficial Air Velocity, Depressant Dosage And Frother Concentration	0.0499	Negative	6
Chrome Recovery	Froth height	0.0085	Negative	13
	Superficial Air Velocity	0.0001	Positive	67
	Frother Concentration	0.0927	Positive	4.3
Chrome Grade	Froth Height	0.0020	Negative	8
	Superficial Air Velocity	0.0002	Positive	18
	Depressant Dosage	0.0001	Positive	41
	Frother Concentration	0.0038	Positive	6
	Froth Height and Depressant dosage	0.0383	Positive	2
	Superficial Air Velocity and Depressant Dosage	0.0003	Negative	15
	Superficial Air Velocity and Frother Concentration	0.0229	Negative	3
	Froth Height Superficial Air Velocity and Depressant Dosage	0.0069	Negative	5
PGM Recovery	Froth Height	0.0002	Negative	27
	Superficial Air velocity	0.0001	Positive	49
	Superficial Air Velocity and Depressant Dosage	0.0055	Negative	11
	Froth Height, Depressant Dosage and Frother Concentration	0.0840	Negative	3
PGM Grade	Froth Height	0.0005	Positive	25
	Superficial Air Velocity	0.0001	Negative	40
	Superficial Air Velocity and Frother Concentration	0.0010	Positive	21

4.5.1 Response of Solids Recovery to Process Parameters

The response of solids recovery was analysed by ANOVA model. The ANOVA model which was used for the response is given in Table 4.2 .The regression equation for the response is given in Equation 4.1. The Equations are shown in terms of coded factors.

$$Solid\ Recovery\left(\frac{g}{min}\right) = 4.58 - 0.92FH + 1.75SAV + 0.5FC \tag{4.1}$$

Where FH = Froth height, SAV= Superficial air velocity and FC= Frother concentration

The individual effect of superficial air velocity and froth height had the greatest impact on solids recovery followed by frother concentration. The depressant dosage had very little effect and was found to be insignificant, and was therefore discarded from the model. No interactive effects were found for the model at a confidence level of 95%. The R^2 value for the model was found to be 0.80 which is considered as a good fit for the model. The effect of a factor is defined as the change in response produced by a change in the level of the factor. This is normally called the "main effect". An interaction between two factors occurs when the difference in response between the levels of one factor is different at all levels from the other factor. The individual and interactive effect of factors and their contribution to solids recovery is given in Figure 4.11. It can be observed that the superficial air velocity had a positive effect on solids recovery and the contribution was larger than that of the other process parameters. After the superficial air velocity the next most important contributor was froth height, which had a negative effect on solids recovery. The frother concentration had a negative effect on solids recovery but the percentage contribution was very small in comparison to the other two factors. No interaction effects were observed for the regression equation for solids recovery.

The order of contribution of factors is given below:

Superficial air velocity>Froth height>Superficial air velocity and Frother>Froth height and Depressant> Depressant > Other effects

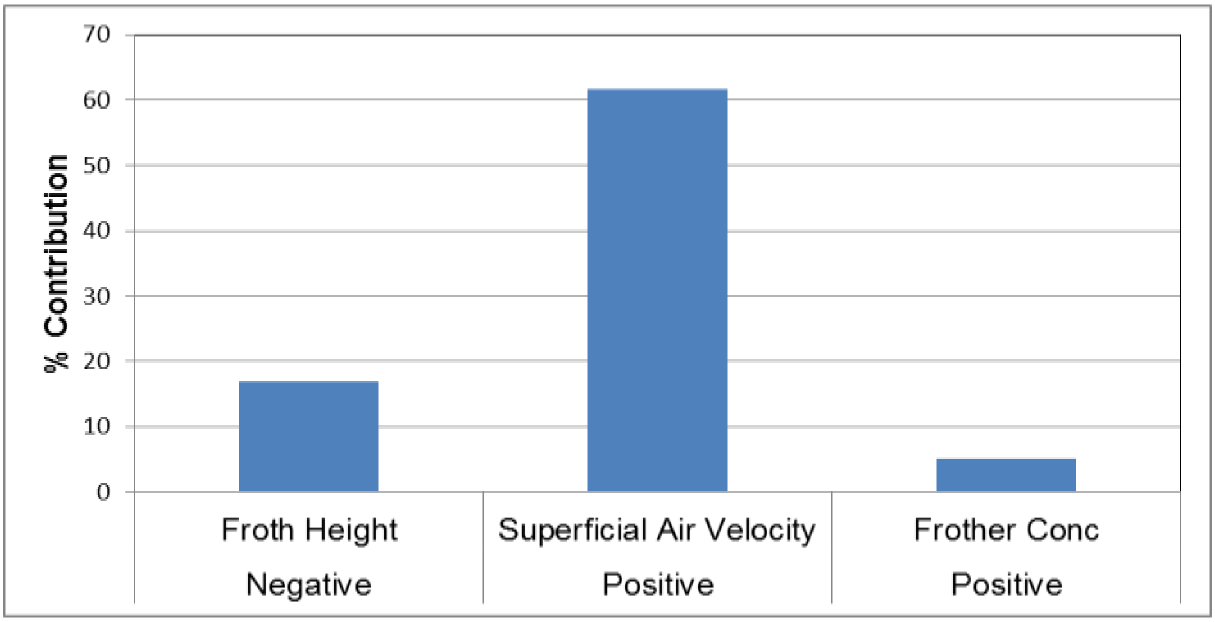


Figure 4.11 Effect of factors and their contribution to solids recovery

4.5.1.1 *Effect of Superficial Air velocity and Froth Height on Solids Recovery*

The following 3D graphs show the interactive effects of the process parameters on the responses as defined by the regression equations. The effect of superficial air velocity and froth height on solids recovery is given below in Figure 4.12, keeping the other two factors viz. depressant dosage and frother concentration at base levels (200 g/t depressant and 25 ppm frother). The figure shows that an increase in superficial air velocity resulted in an increase in solids recovery at high and low froth heights. Similarly, an increase in froth height resulted in a decrease in solids recovery at high and low superficial air velocities.

Similar graphs showing the results obtained for other factors at high and low levels are shown in Appendix-B. Superficial air velocity and froth height had the same effect on solids recovery at base, high and low levels.

The results can be summarised as:

- The solids recovery increased with an increase in superficial air velocity and decreased with an increase in froth height.
- Superficial air velocity had a greater effect on solids recovery compared to froth height.

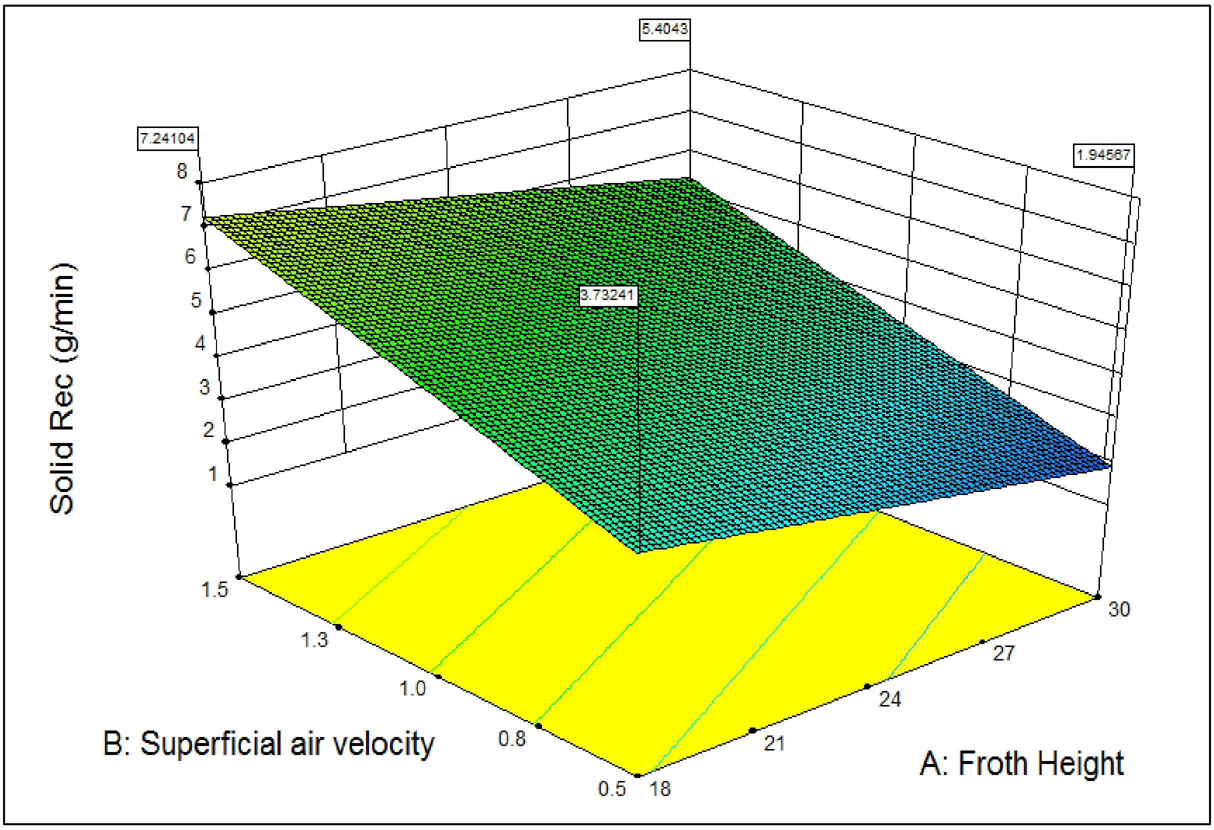


Figure 4.12 Effect of superficial air velocity and froth height on solids recovery keeping other factors at base levels (200 g/t depressant & 25sppm frother)

4.5.1.2 Effect of Superficial Air velocity and Depressant Dosage on Solids Recovery

The effect of superficial air velocity and depressant dosage is given in Figure 4.13. Figure 4.13 shows that an increase in superficial air velocity resulted in an increase in solids recovery at high and low depressant dosage. However, the depressant dosage had no effect on solids recovery at high and low superficial air velocities, since depressant dosage was not a significant factor in the regression equation. The effects obtained at high and low levels are shown in Appendix-B

The results can be summarised as:

- The superficial air velocity had a major effect on the solids recovery at all the levels of factors.
- The depressant dosage had a negligible effect at all the levels of factors.

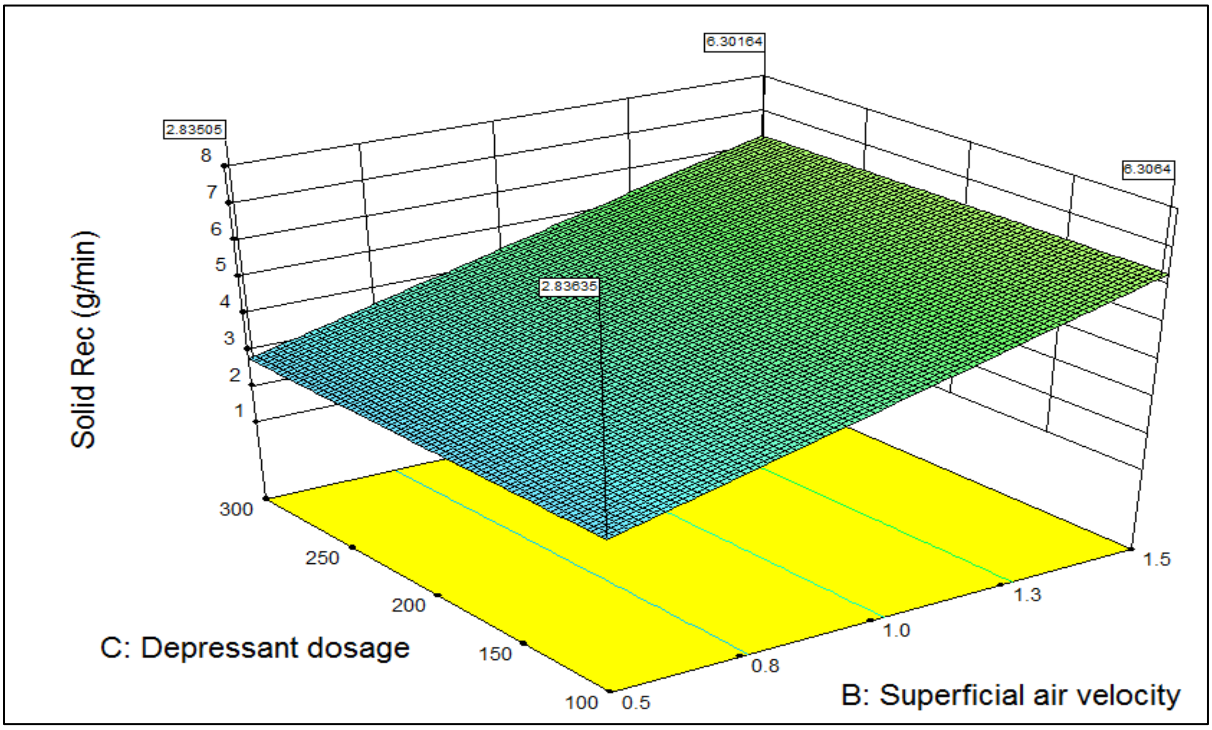


Figure 4.13 Effect of superficial air velocity and depressant dosage on solids recovery keeping other factors at base level (25 ppm frother and 24 cm froth height)

4.5.1.3 Effect of Superficial Air velocity and Frother Concentration on Solids Recovery

The effect of superficial air velocity and frother concentration is given in Figure 4.14, keeping the other two factors viz. froth height and depressant dosage at base levels (24 cm froth height and 200 g/t depressant). Figure 4.14 shows that an increase in superficial air velocity resulted in an increase in solids recovery at high and low frother concentrations. Similarly, an increase in frother concentration resulted in an increase in solids recovery at both high and low levels of superficial air velocity. However, the effects of frother dosage are small compared to the effects of air flow rate. Similar observations were made at high and low levels of the other factors (Appendix-B).

The results can be summarised as:

- The solids recovery was directly proportional to the superficial air velocity and frother concentrations at high low and base levels.
- The rate of change of solids recovery with an increase in superficial air velocity was greater than the rate of change of solids recovery for increased frother concentration.

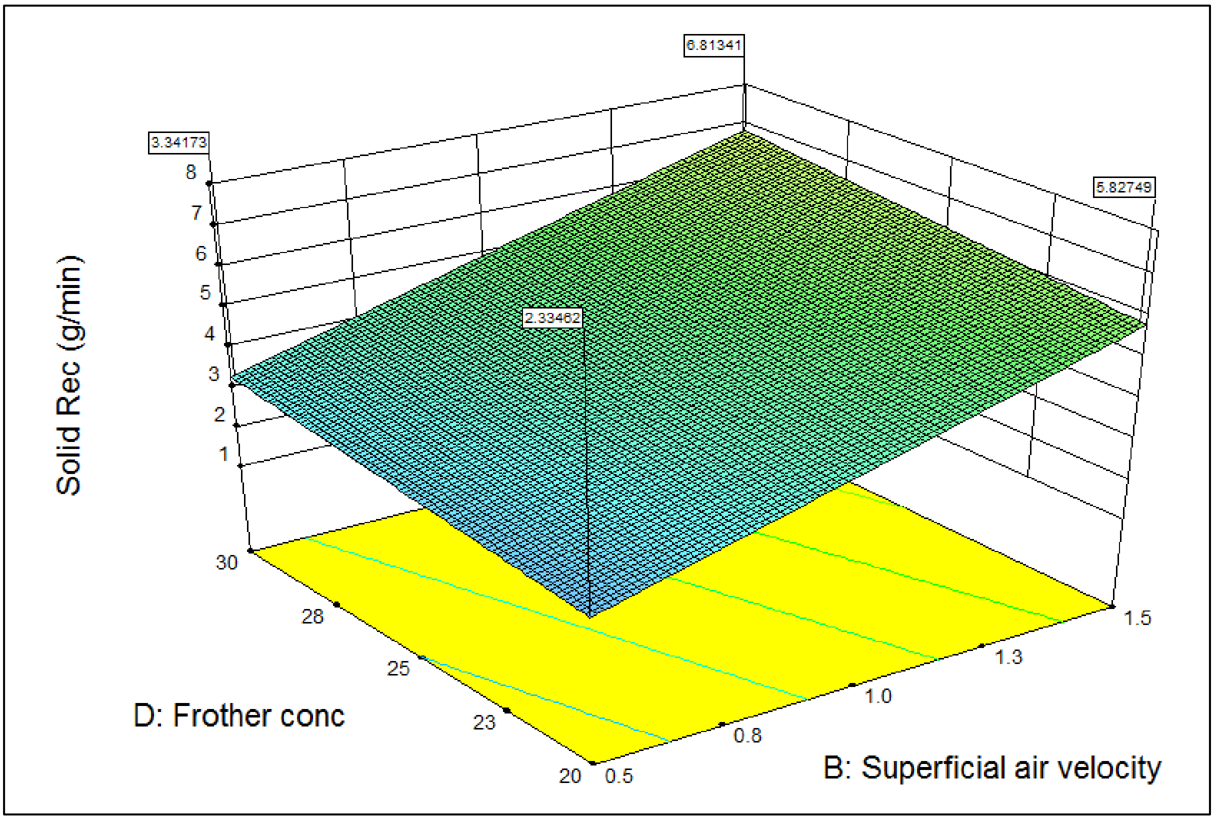


Figure 4.14 Effect of superficial air velocity and frother concentration on solids recovery keeping other factors at base level (200g/t depressant & 24 cm froth height)

4.5.1.4 Effect of Froth Height and Depressant Dosage on Solids Recovery

The effect of froth height and depressant dosage is given below in Figure 4.15, keeping the other two factors viz. superficial air velocity and frother concentration at base levels (1 cm/sec superficial air velocity and 25 ppm frother). Figure 4.15 shows that, as expected, there was no change in solids recovery when changing depressant dosage at high and low froth heights. There was a decrease in solids recovery with an increase in froth height. Appendix-B shows similar observations at low and high levels of the other factors.

The results can be summarised as:

- An increase in froth height resulted in a decrease in solids recovery at all levels of factors.
- There was no change in solids recovery with changes in depressant dosage.

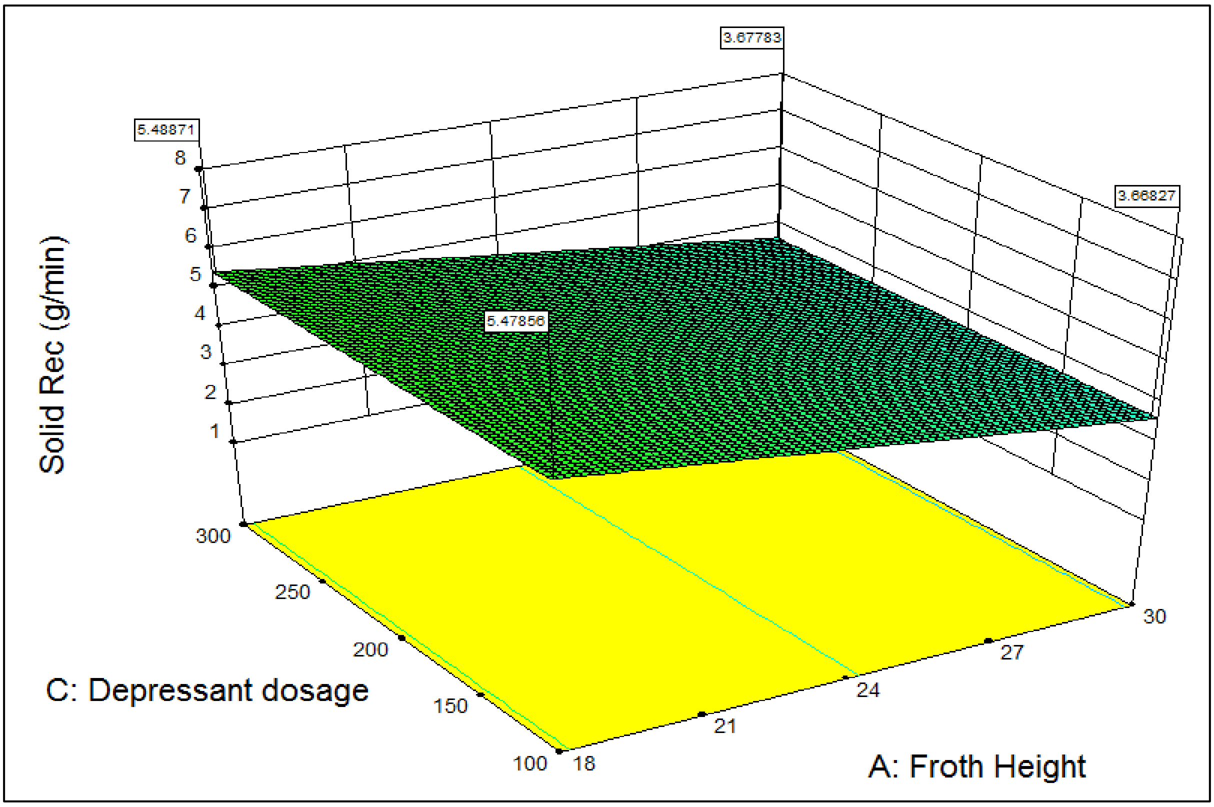


Figure 4.15 Effect of froth height and depressant dosage on solids recovery keeping other factors at base level (1cm/sec superficial air velocity & 25 ppm frother)

4.5.1.5 Effect of Froth Height and Frother Concentration on Solids Recovery

The effect of froth height and frother concentration is given in Figure 4.16, keeping the other two factors viz. superficial air velocity and depressant dosage at base levels (1 cm/sec superficial air velocity and 200 g/t depressant dosage). Figure 4.16 shows that solids recovery increased with an increase in frother concentration at high and low froth heights. In the case of froth height the solids recovery decreased with an increase in froth height at both high and low frother concentrations. Froth height had a greater effect on solids recovery than frother concentration. Similar effects are shown at low and high levels of the other factors in Appendix-B

The results can be summarised as:

- Solids recovery was directly proportional to the frother concentration and inversely proportional to the froth height.

Froth height had a greater effect on solids recovery than frother concentration.

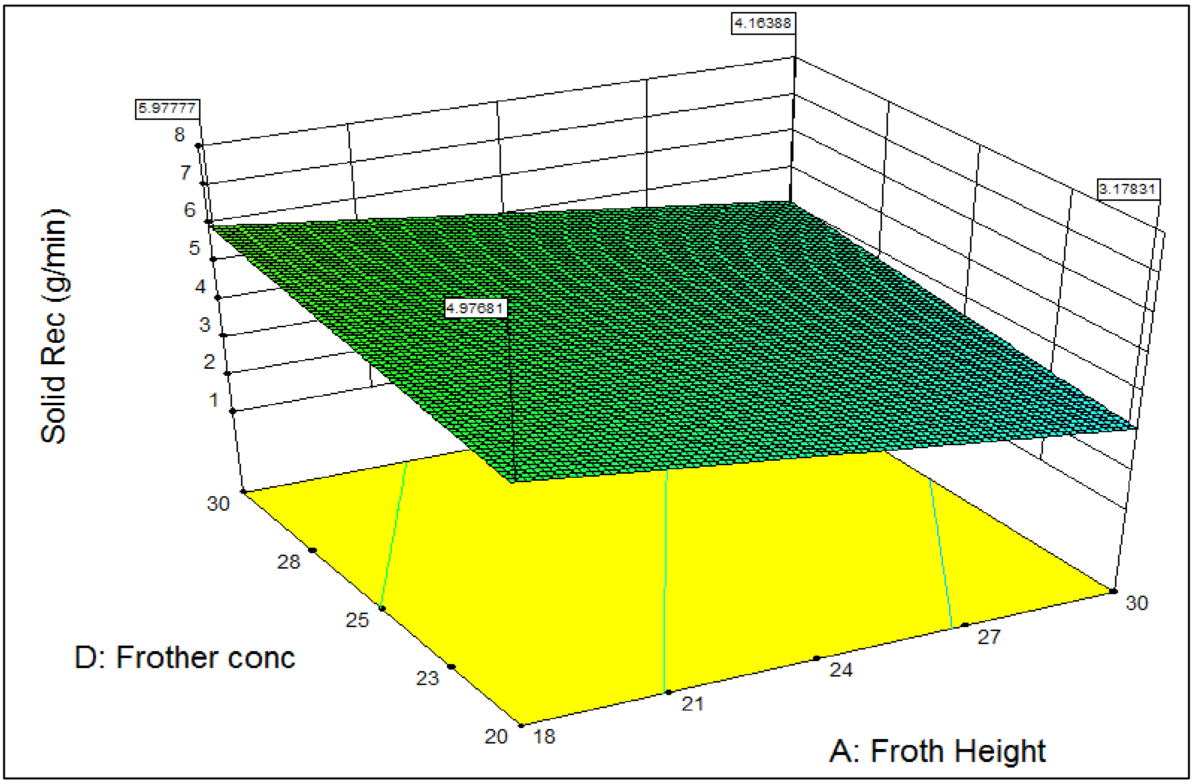


Figure 4.16 Effect of froth height and frother concentration on solids recovery keeping other factors at base levels (200g/t depressant &1 cm/sec superficial air velocity)

4.5.1.6 Effect of Depressant Dosage and Frother Concentration on Solids Recovery

The effect of depressant dosage and frother concentration is given in Figure 4.17, keeping the other two factors viz. superficial air velocity and froth height at base levels (1 cm/sec superficial air velocity and 24 cm froth height). Figure 4.17 shows that there was a small increase in solids recovery with an increase in frother concentration at high and low depressant dosage. Depressant dosage had no effect on the solids recovery. Similar observations are shown in Appendix-B at low and high levels of the other factors.

The results can be summarised as:

- An increase in frother concentration resulted in an increase in solids recovery at both high and low depressant dosages.
- Depressant dosage had no effect on solids recovery.

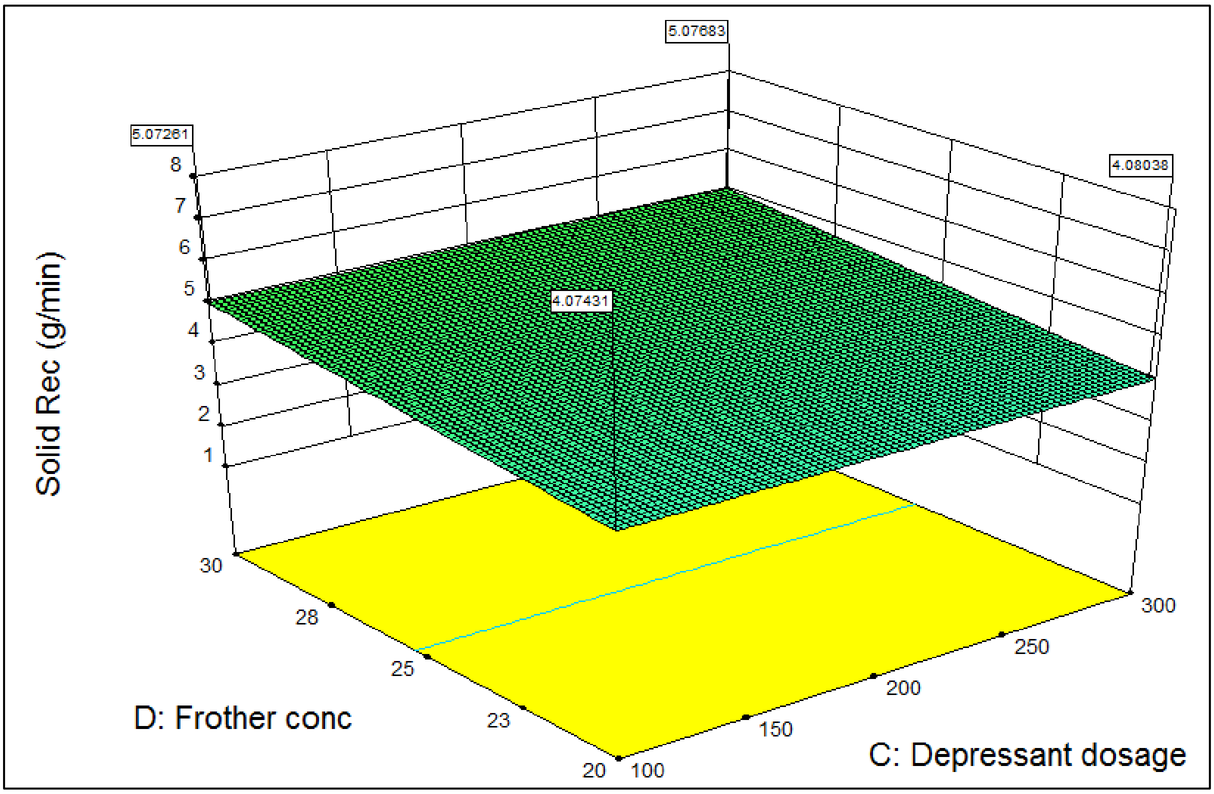


Figure 4.17 Effect of depressant dosage and frother concentration on solids recovery keeping other factors at base level (1 cm/sec superficial air velocity & 24 cm froth height)

4.5.2 Response of Water Recovery to Process Parameters

The response of water recovery was analysed by ANOVA model. The regression equation for the response is given in Equation 4.2. The confidence level is 95%.The R^2 value was found to be 0.82 and considered as a satisfactory fit for the model

$$Water\ Rec(g/min) = 171.59 - 38.47 * FH + 57.75 * SAV + 43.03 * FC - 21.26 * SAV * DD * FC \qquad (4.2)$$

The individual and interactive effects of factors and their contribution to water recovery is given in Figure 4.18. Figure 4.18 shows that the superficial air velocity had a positive effect on water recovery and the contribution was greater compared to other process parameters. After the superficial air velocity, the next most important contributors were frother concentration and froth height, which had positive and negative effects. The combined effect of superficial air velocity, depressant dosage and frother concentration had the lowest contribution compared to other factors, which had a negative influence on water recovery. The individual effect of depressant dosage had no effect on water recovery.

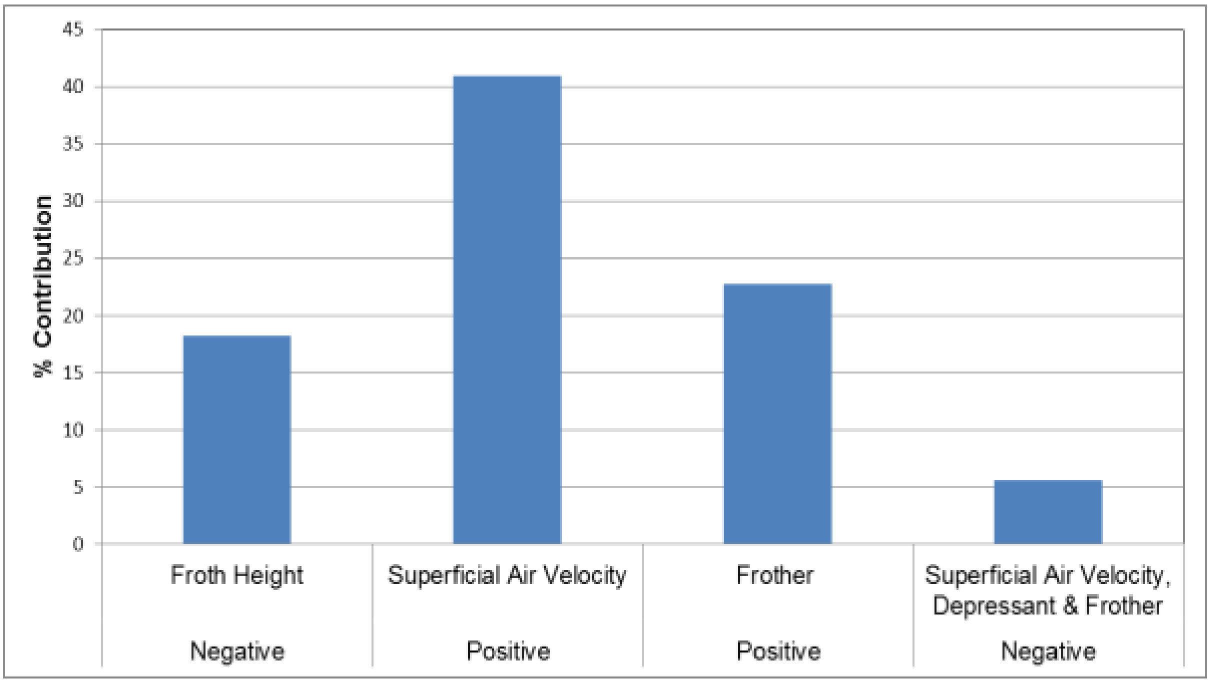


Figure 4.18 Effect of factors and their contribution on water recovery

The order of percentage contribution of factors for water recovery is as follows

Superficial air velocity> > Frother>Froth height > Superficial air velocity, Depressant & Frother

4.5.2.1 *Effect of Superficial Air velocity and Froth Height on Water Recovery*

The effect of superficial air velocity and froth height is given below in Figure 4.19, keeping the other two factors viz. depressant dosage and frother concentration at base levels (200 g/t depressant and 25 ppm frother). From Figure 4.19, it is observed that an increase in superficial air velocity resulted in an increase in water recovery at high and low froth heights. Conversely, an increase in froth height resulted in a decrease in water recovery at high and low superficial air velocities. Appendix-C shows similar results in the case of high and low levels of the other factors.

The results can be summarised as:

- The water recovery increased with an increase in superficial air velocity and decreased with an increase in froth height.
- The superficial air velocity had a greater effect on water recovery than froth depth.

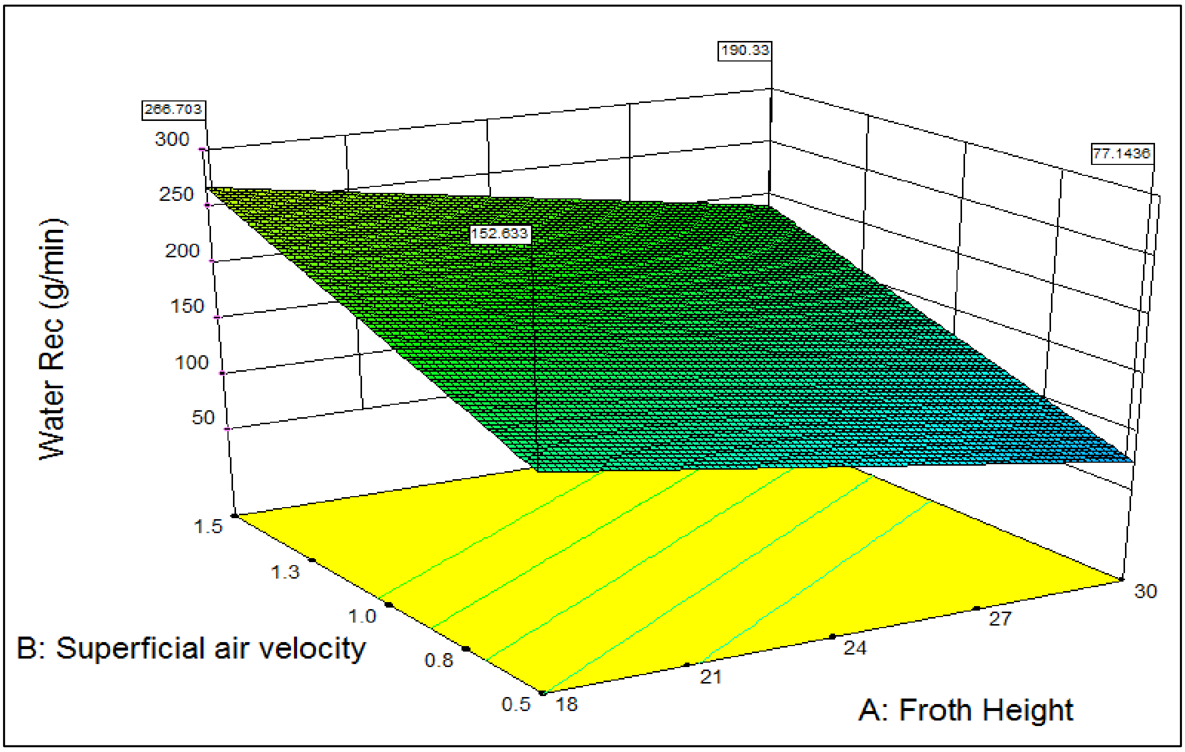


Figure 4.19 Effect of superficial air velocity and froth height on water recovery keeping other factors at base levels (200 g/t depressant & 25 ppm frother)

4.5.2.2 Effect of Superficial Air velocity and Depressant Dosage on Water Recovery

The interactive effects of superficial air velocity and depressant dosage is given in Figures 4.20, 4.21 and 4.22, respectively where the other factors are at low, base and high levels. Figure 4.20 (low level) shows that an increase in superficial air velocity resulted in an increase in water recovery at high and low depressant dosage. An increase in depressant dosage resulted in an increase in water recovery at high superficial air velocity and vice versa at low superficial air velocity. When the levels of the other two factors (froth height and frother concentration) were set to their midpoint levels, (Figure 4.21) the depressant dosage had no effect on water recovery at low and high level of superficial air velocities. In the case of high levels of froth height and frother concentration (Figure 4.22), water recovery decreased with increasing depressant dosage at high superficial air velocity and vice versa at low superficial air velocity. This is the opposite of the effect of depressant dosage at the low levels of the other two factors. The observations are summarized in table 4.3

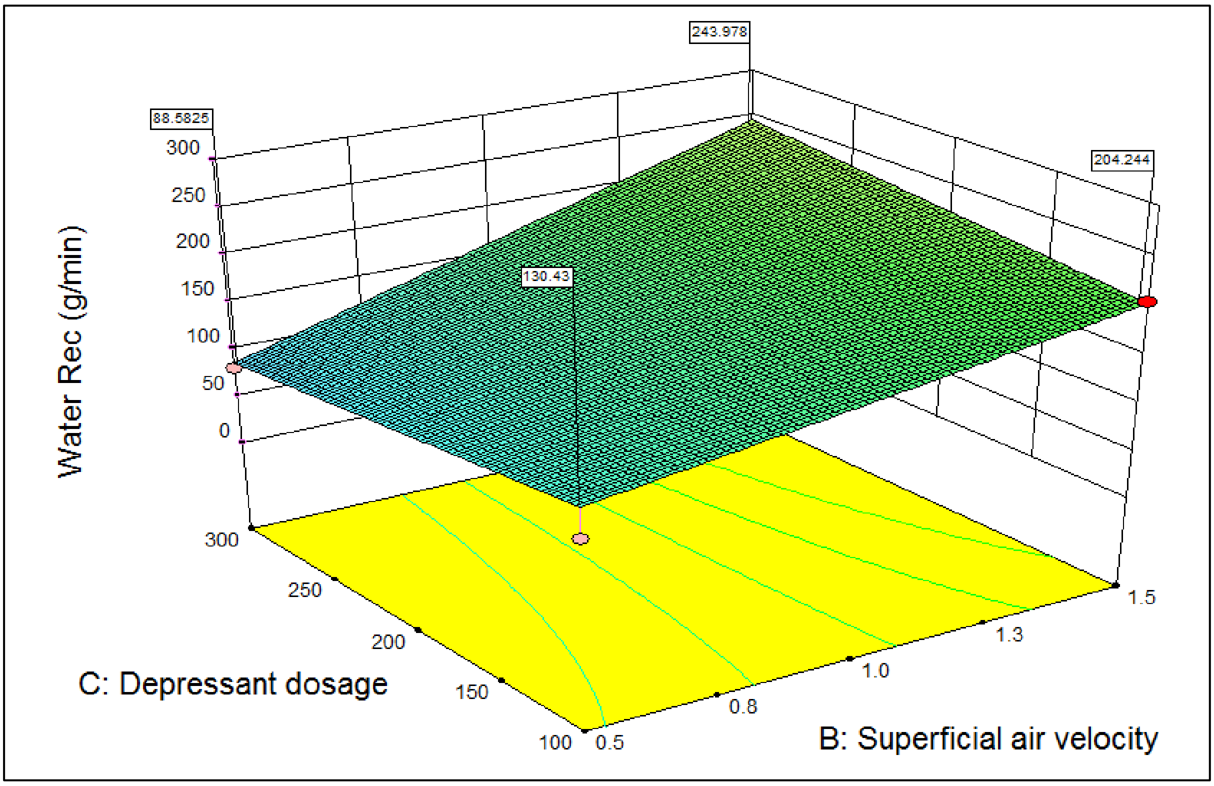


Figure 4.20 Effect of superficial air velocity and depressant dosage on water recovery keeping other factors at low level (18 cm froth height & 20 ppm frother)

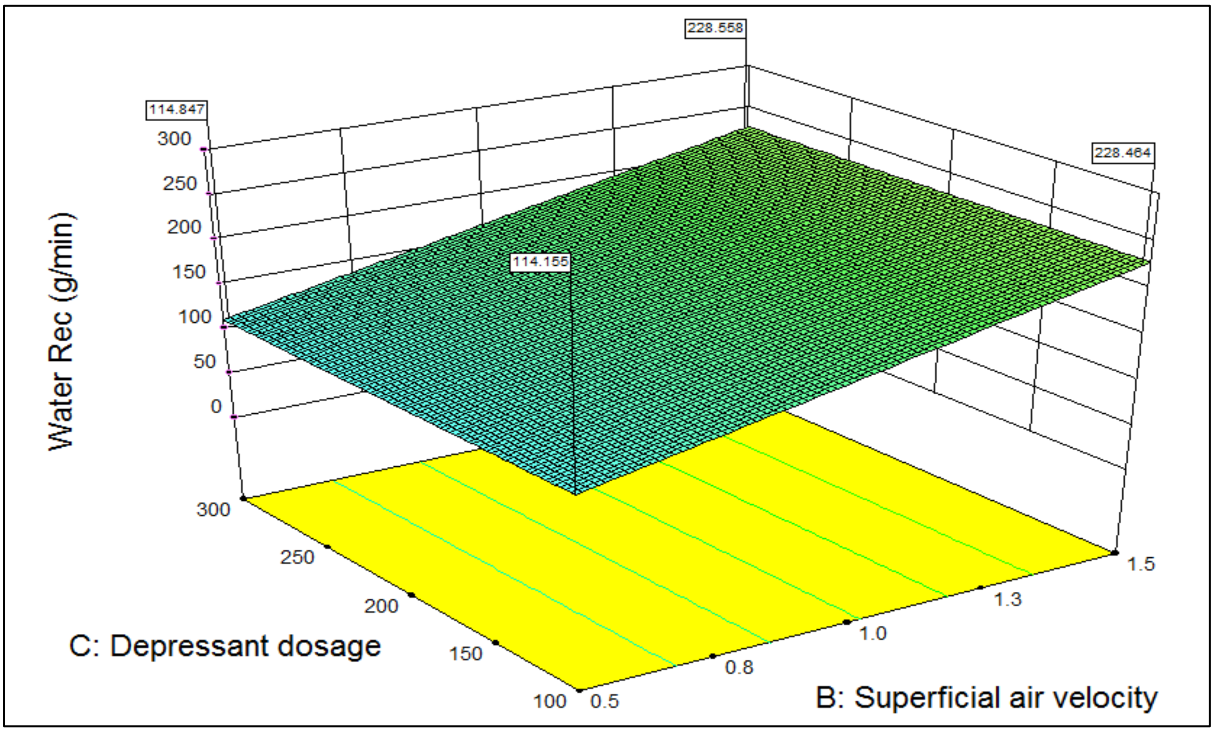


Figure 4.21 Effect of superficial air velocity and depressant dosage on water recovery keeping other factors at base level (24 cm froth height & 25 ppm frother)

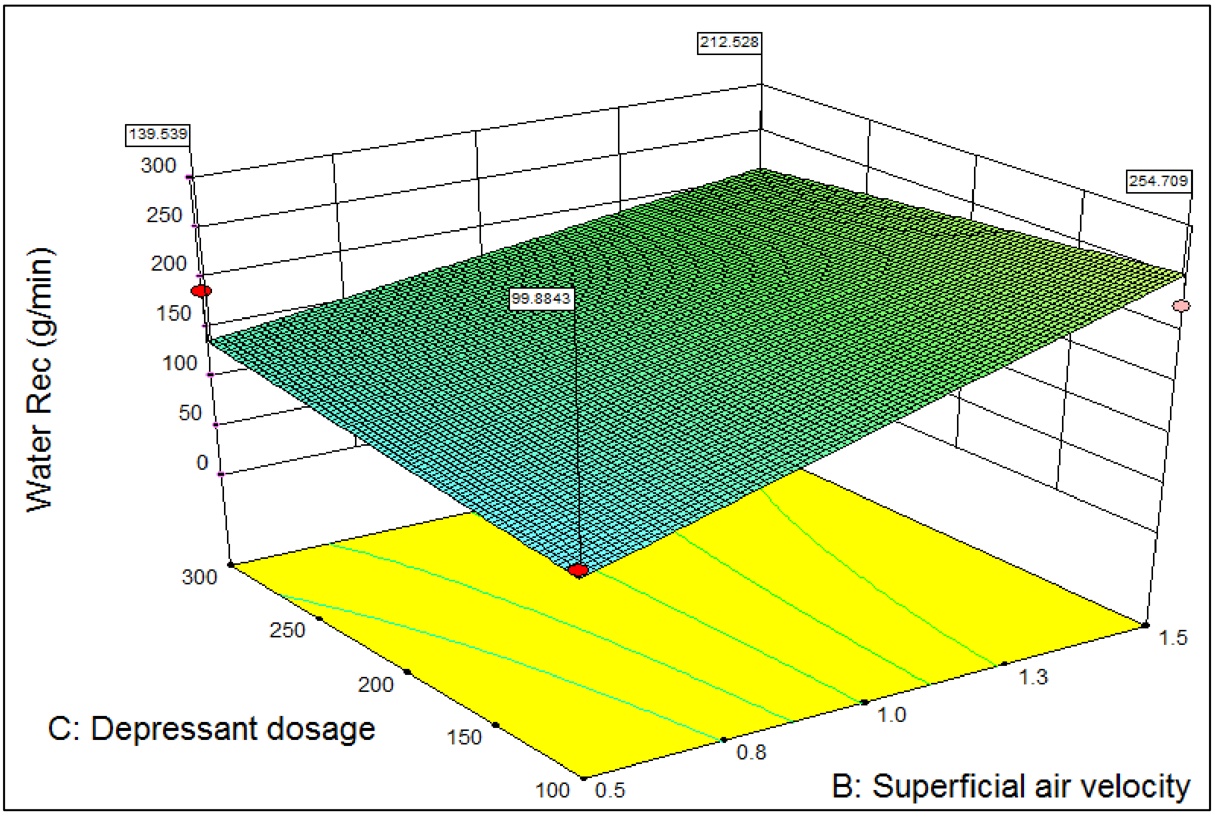


Figure 4.22 Effect of superficial air velocity and depressant dosage on water recovery keeping other factors at high level (30 cm froth height & 30 ppm frother)

Table 4.3 Summarized results of superficial air velocity and depressant dosage on water recovery

Constant factors & levels	Variable Factors		Effects on Response
Froth height and Frother conc	**Superficial Air Velocity**	**Depressant dosage**	**Water Recovery**
@ Low level (18 cm & 20 ppm)	Low to High	Low level	Increases
	Low to High	High Level	Increases
	Low Level	Low to high	Decreases
	High Level	Low to High	Increases
@ Base level (24 cm & 25 ppm)	Low to High	Low level	Increases
	Low to High	High Level	Increases
	Low Level	Low to high	No change
	High Level	Low to High	No change
@ High level (30 cm & 30 ppm)	Low to High	Low level	Increases
	Low to High	High Level	Increases
	Low Level	Low to high	Increases
	High Level	Low to High	Decreases

4.5.2.3 Effect of Superficial Air velocity and Frother Concentration on Water Recovery

The effect of superficial air velocity and frother concentration on water recovery is given in Figure 4.23, keeping the other factors at base levels. From Figure 4.23 (base level) it can be observed that an increase in superficial air velocity resulted in an increase in water recovery at high and low frother concentrations. Water recovery increased with increasing frother concentration at high and low superficial air velocities. Similar observations are shown in Appendix-C with the other factors at low and high levels.

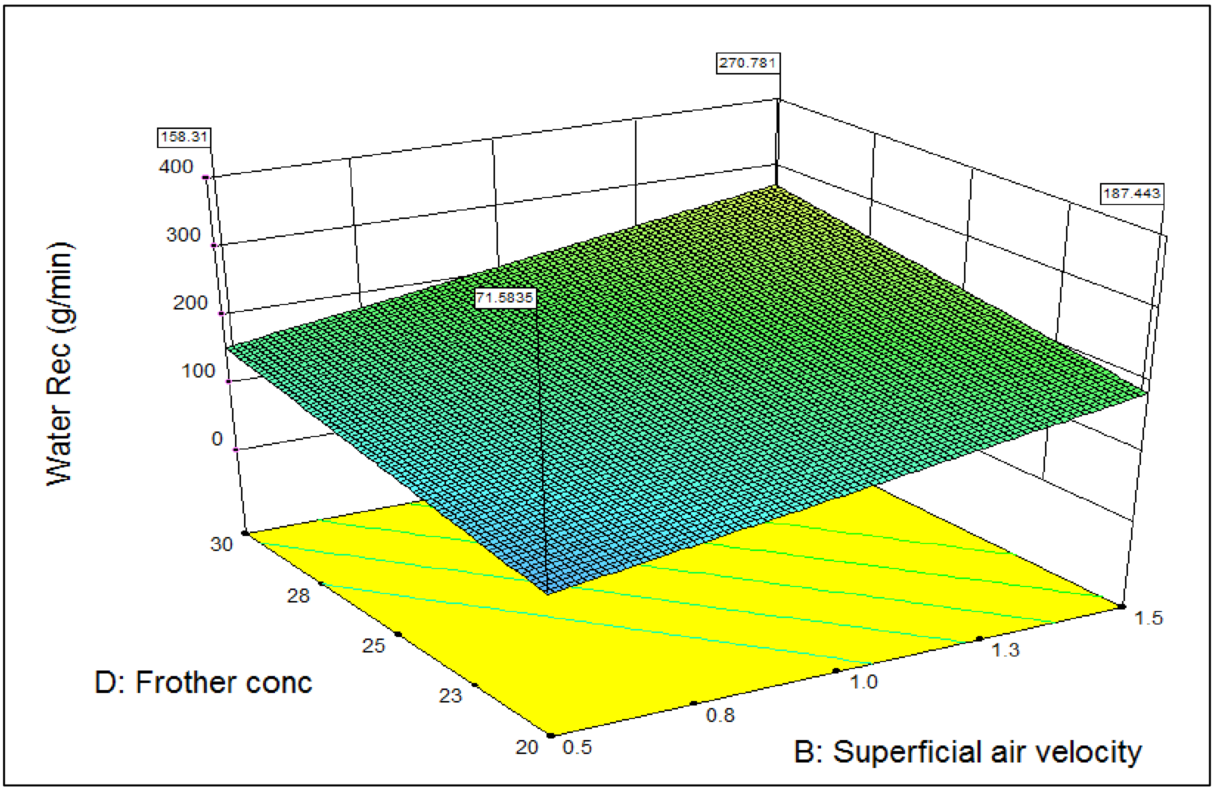


Figure 4.23 Effect of superficial air velocity and frother concentration on water recovery keeping other factors at base level (24 cm froth height & 200 g/t depressant)

4.5.2.4 Effect of Froth Height and Depressant Dosage on Water Recovery

The effect of froth height and depressant dosage on water recovery was investigated keeping the other factors at low, base and high level. The effect of froth height and depressant dosage on water recovery was found to be similar on all the levels of other factors (low, base and high). From Figure 4.24 it was observed that water recovery decreased with an increase in froth height both at high and low depressant dosage. There was no change in water recovery with an increase in depressant dosage. Similar observations were found in case of other factors at low and base levels (Appendix-C).

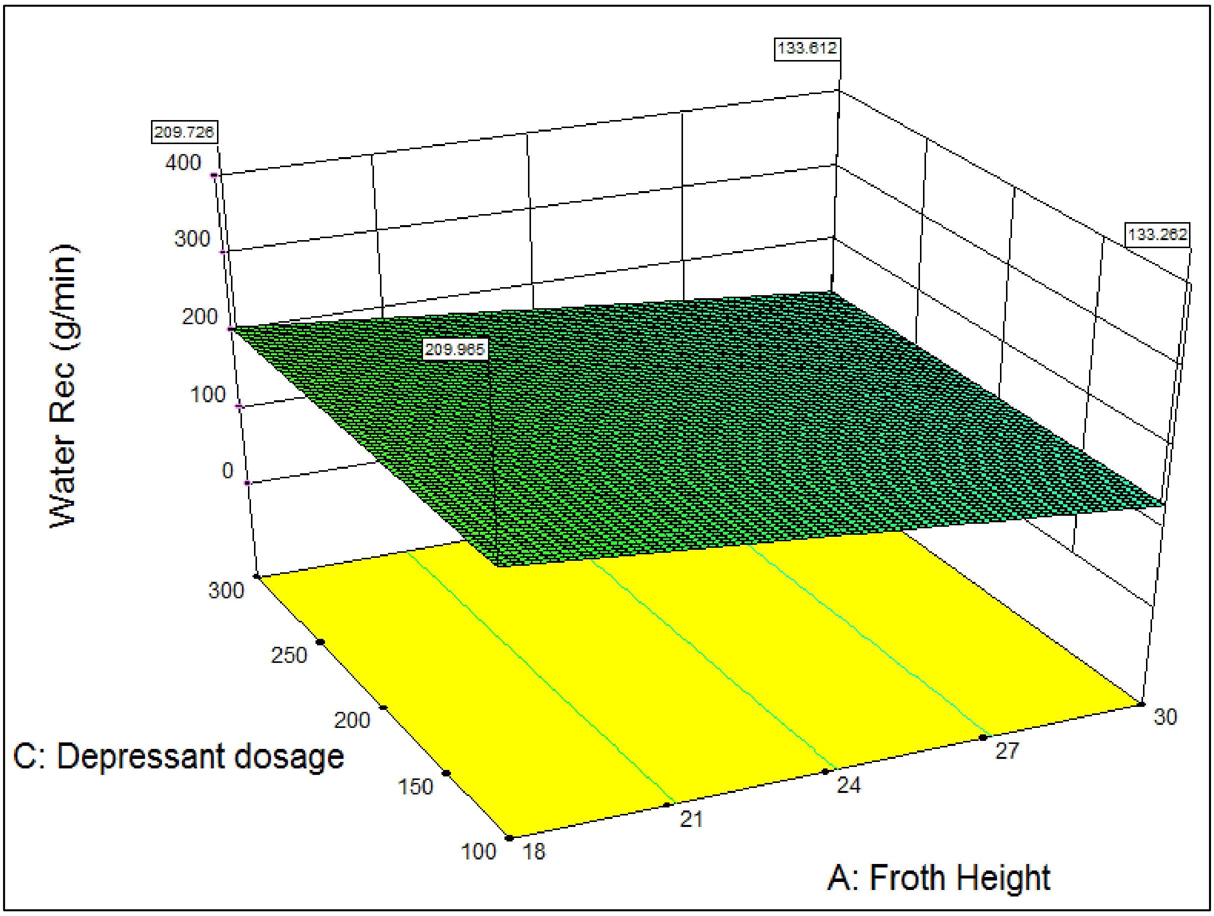


Figure 4.24 Effect of froth height and depressant dosage on water recovery keeping other factors at high level (1 cm/sec superficial air velocity & 25 ppm frother concentration)

4.5.2.5 Effect of Froth Height and Frother Concentration on Water Recovery

The effect of froth height and frother concentration on water recovery was investigated keeping the other factors at low, base and high level. The effect of froth height and frother concentration on water recovery was found to be similar for all three levels (Appendix-C). From Figure 4.25 it can be observed that water recovery decreased with an increase in froth height both at high and low frother concentrations. In case of frother concentration, water recovery increased with an increase in frother concentration at low and high froth heights.

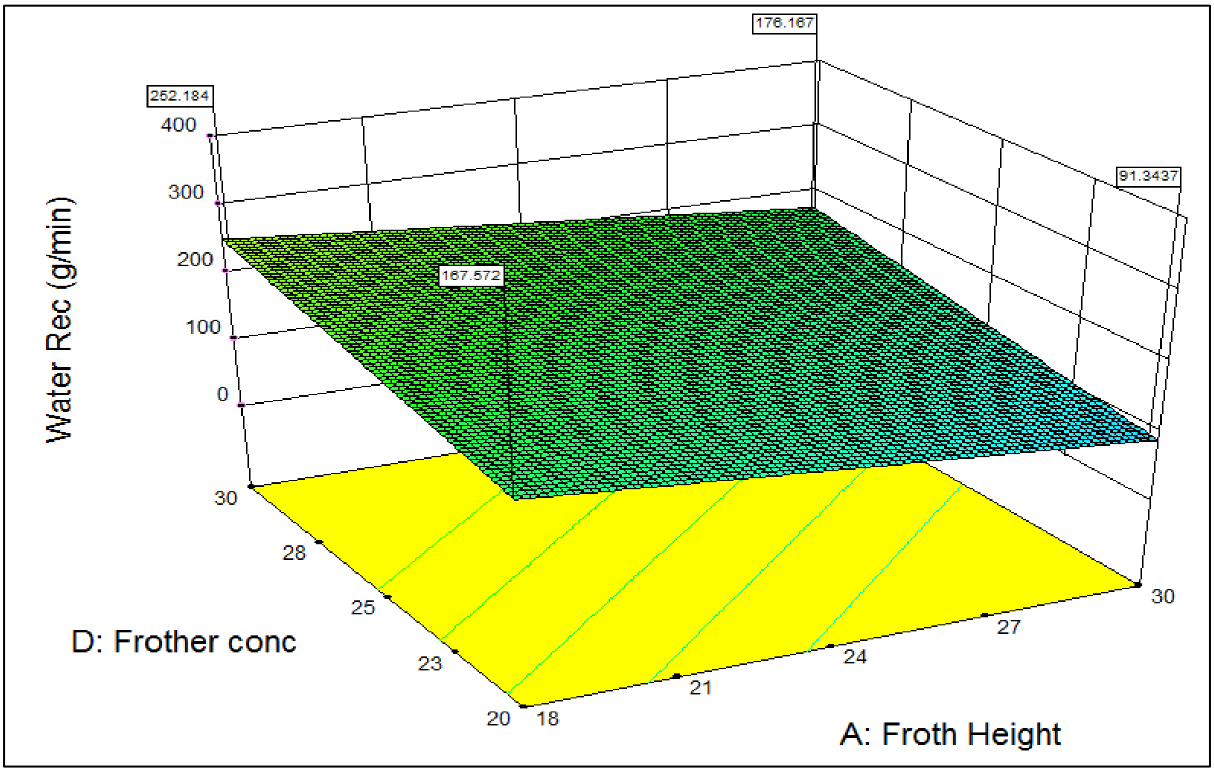


Figure 4.25 Effect of froth height and frother concentration on water recovery keeping other factors at base level (1 cm/sec superficial air velocity & 200 g/t of depressant dosage)

4.5.2.6 Effect of Depressant Dosage and Frother Concentration on Water Recovery

The effects of depressant dosage and frother concentration on water recovery were investigated keeping the other factors at low, base and high level. The effect of frother concentration on water recovery was found to be similar for all the levels of the other factors. This is shown in Figures 4.26, 4.27 and 4.28, respectively. Figure 4.26 shows that water recovery increased with an increase in frother concentration at both at high and low depressant dosage. Water recovery decreased with an increase in depressant dosage at low frother concentration and vice versa at high frother concentration. Figure 4.27 shows that the depressant dosage had little effect on water recovery at both high and low frother concentrations. While at high levels of the other two factors (Figure 4.28), the water recovery increased with increasing frother concentration at low depressant dosage and vice versa at high depressant dosage. The summarized results are given in Table 4.4

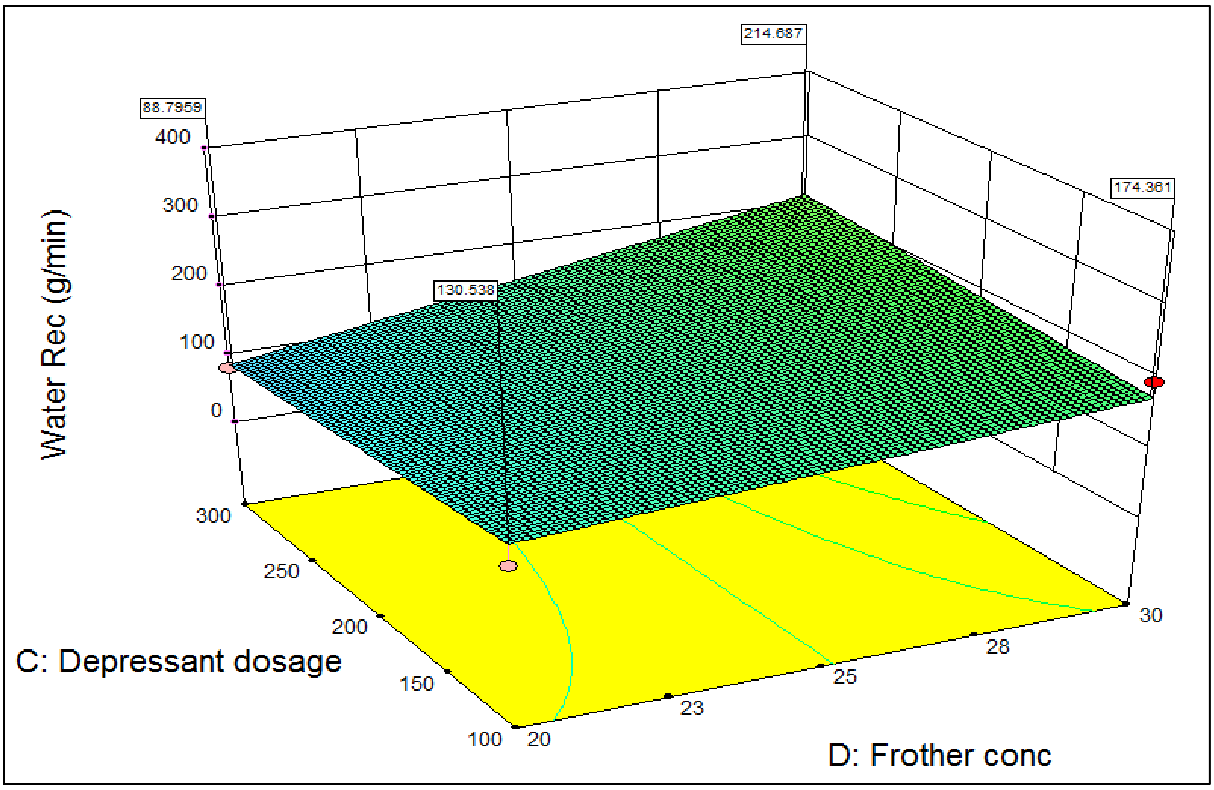


Figure 4.26 Effect of depressant dosage and frother concentration on water recovery keeping other factors at low level (0.5 cm/sec superficial air velocity & 18 cm of froth height)

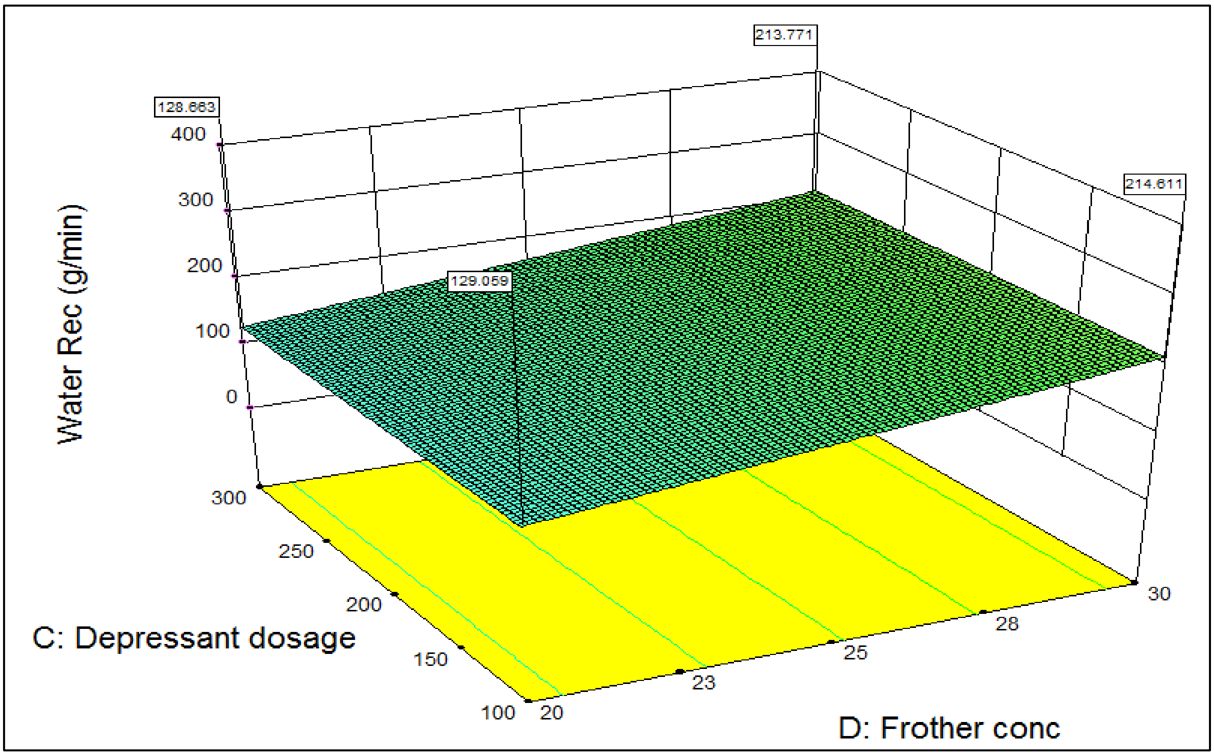


Figure 4.27 Effect of depressant dosage and frother concentration on water recovery keeping other factors at base level (1 cm/sec superficial air velocity & 24 cm of froth height)

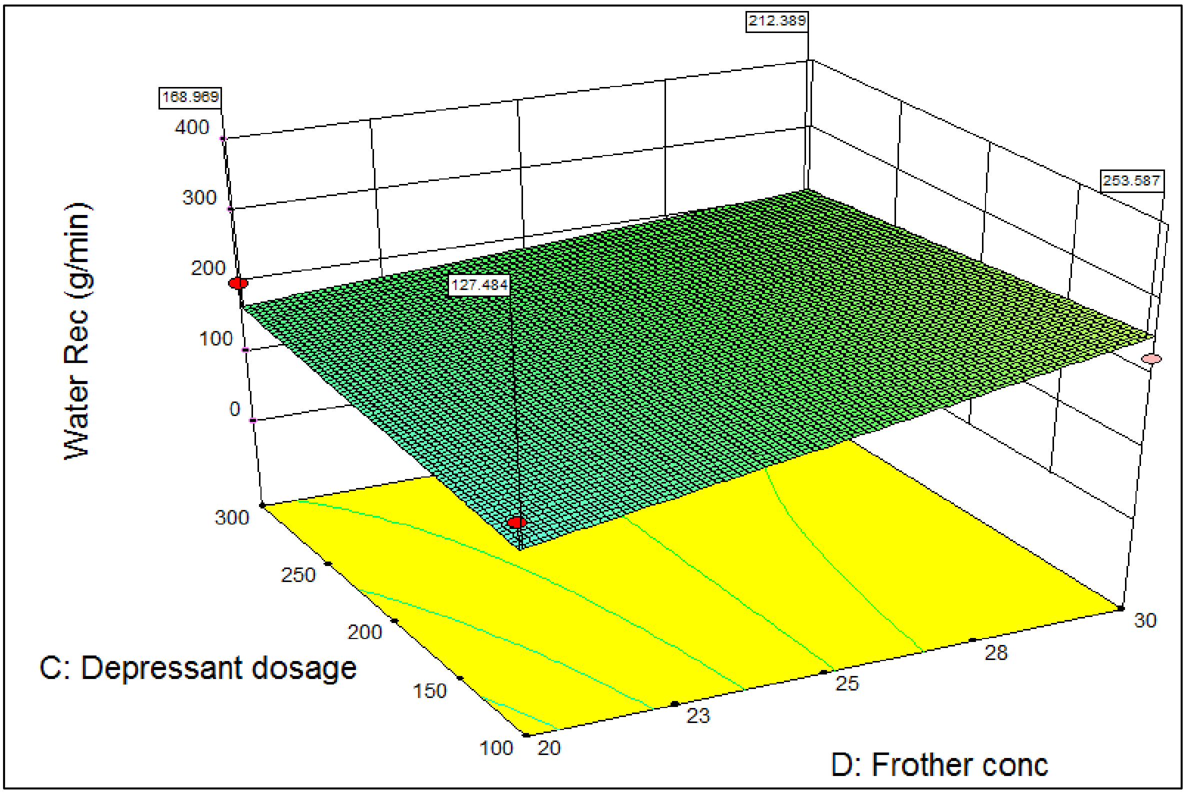


Figure 4.28 Effect of depressant dosage and frother concentration on water recovery keeping other factors at base level (1.5 cm/sec superficial air velocity & 30 cm of froth height)

Table 4.4 Summarized results of depressant dosage and frother concentration on water recovery

Constant factors & levels	Variable Factors		Effects on Response
Superficial air velocity and Froth height	**Depressant dosage**	**Frother concentration**	**Water Recovery**
@ Low level (0.5 cm/sec & 18 cm)	Low to High	Low level	Decreases
	Low to High	High Level	Increases
	Low Level	Low to high	Increases
	High Level	Low to High	Increases
@ Base level (1 cm/sec & 24 cm)	Low to High	Low level	No change
	Low to High	High Level	No change
	Low Level	Low to high	Increases
	High Level	Low to High	Increases
@ High level (1.5 cm/sec & 30 cm)	Low to High	Low level	Increases
	Low to High	High Level	Decreases
	Low Level	Low to high	Increases
	High Level	Low to High	Increases

4.5.3 Response of Chrome Recovery to Process Parameters

The response of chrome recovery was investigated for the different process parameters. The chrome is expressed here in terms of Cr_2O_3

$$Chrome\ Rec\left(\frac{g}{min}\right) = 0.62 - 0.13FH + 0.30SAV + 0.077FC \qquad (4.3)$$

Equation 4.3 gives the regression equation that best fits the experimental data. The R^2 value for the model was found to be 0.82 which can be considered as a good fit. The individual effects of superficial air velocity and froth height had the greatest impact on chrome recovery, followed by frother concentration. The depressant dosage had no effect on chrome recovery. Therefore, it was discarded from the model. There were no interactive effects observed in this model.

Individual effects of factors and their contribution to chrome recovery is given in Figure 4.29. Figure 4.29 shows that the superficial air velocity had a positive effect on chrome recovery and the contribution was greater (67%) than the other process parameters. The second most important contributor was froth height with 15% contribution, which had a negative influence on chrome recovery. The contribution of frother concentration was found to be 8%.

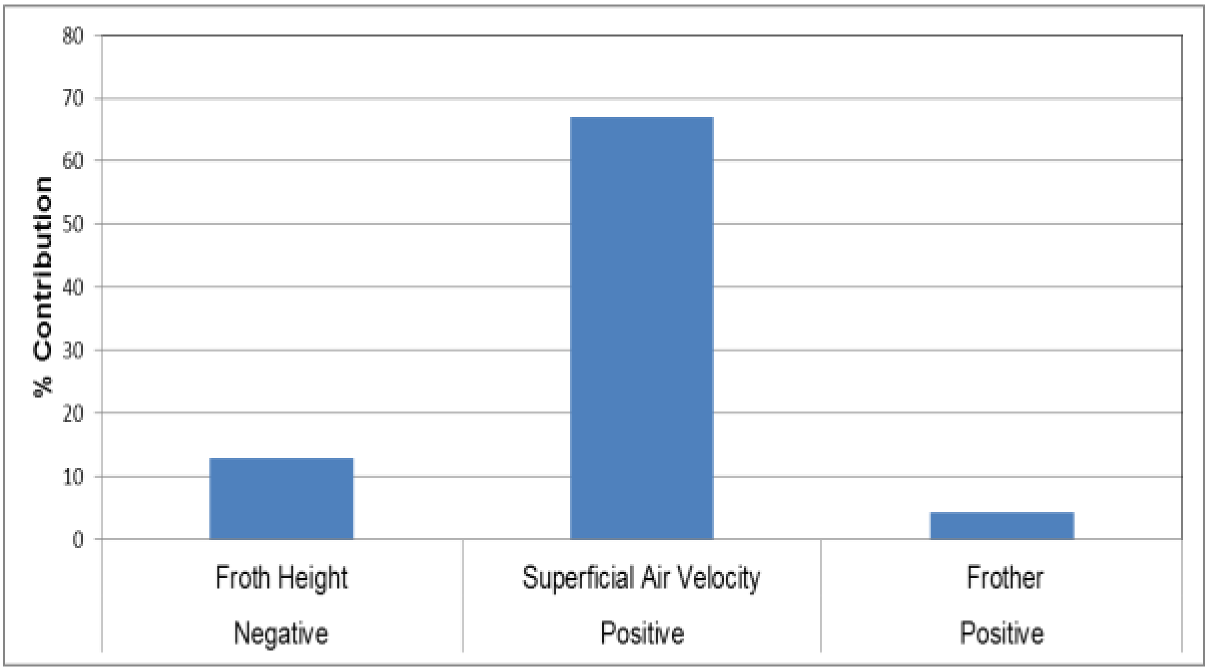


Figure 4.29 Effect of factors and their contribution on chrome recovery

The order of percentage contribution of factors for chrome recovery is as follows

Superficial Air Velocity> Froth height> Frother

4.5.3.1 Effect of Superficial Air velocity and Froth Height on Chrome Recovery

The effect of superficial air velocity and froth height on chrome recovery is given in Figure 4.30 keeping the other two factors viz. depressant dosage and frother concentration at base levels (200 g/t depressant and 25 ppm frother). From Figure 4.30, it is observed that an increase in superficial air velocity resulted in an increase in chrome recovery at high and low froth heights. In the case of froth height, an increase in froth height resulted in a decrease in chrome recovery at high and low superficial air velocities. Similar observations were found with superficial air velocity and froth height keeping other factors at high and low levels (Appendix-D).

The results can be summarised as:

- The chrome recovery increased with an increase in superficial air velocity and decreased with an increase in froth height.
- The superficial air velocity had a greater effect on chrome recovery than froth height.

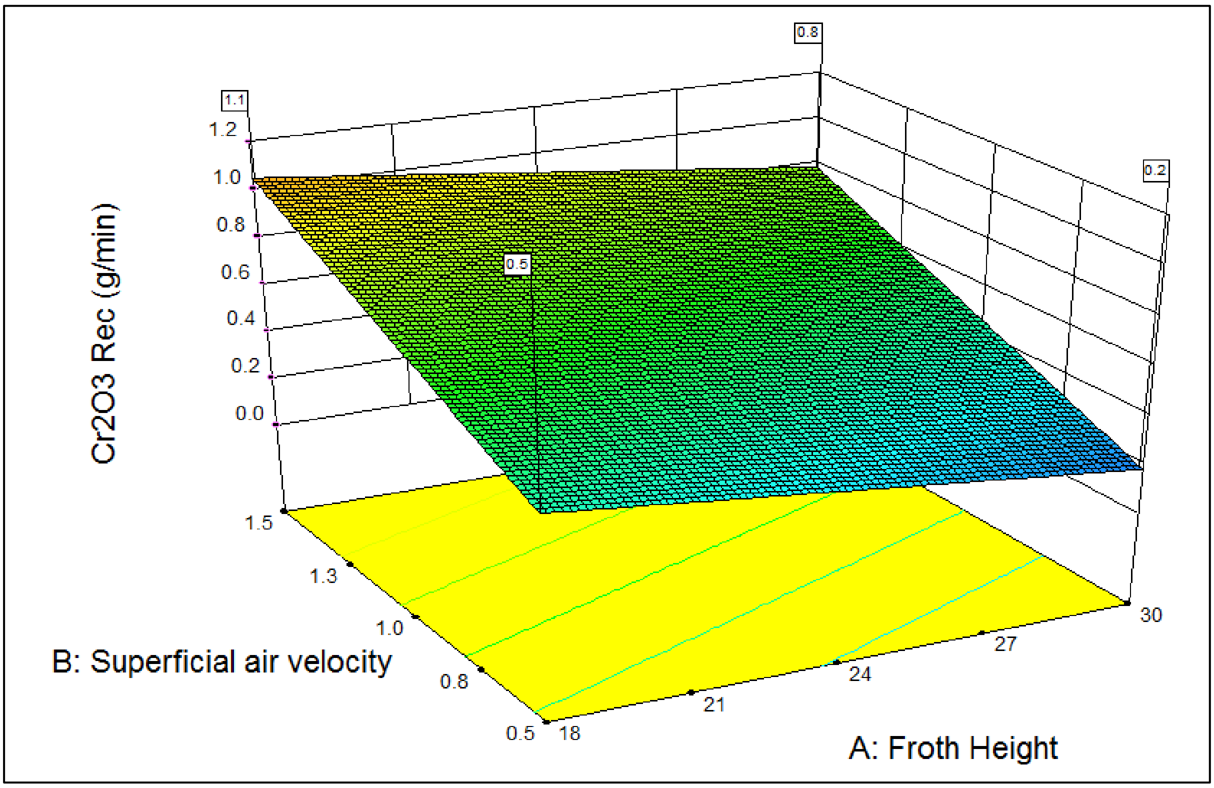


Figure 4.30 Effect of superficial air velocity and froth height on chrome recovery keeping other factors at base levels (200 g/t depressant & 25 ppm frother)

4.5.3.2 Effect of Superficial Air velocity and Depressant Dosage on Chrome Recovery

The effect of superficial air velocity and depressant dosage on chrome recovery is given in Figure 4.31, keeping the other factors at base levels (24 cm froth height and 25 ppm frother). Figure 4.31 shows that chrome recovery increased with an increase in superficial air velocity at both high and low depressant dosages. Whereas there was no change observed in chrome recovery with an increase in depressant dosage both at high and low superficial air velocities. Similar observations are shown in Appendix-D with the other factors at high and low levels. The results can be summarised as:

- The chrome recovery increased with an increase in superficial air velocity at high and low levels of depressant dosage.
- The chrome recovery remained unaffected with changes in depressant dosage.

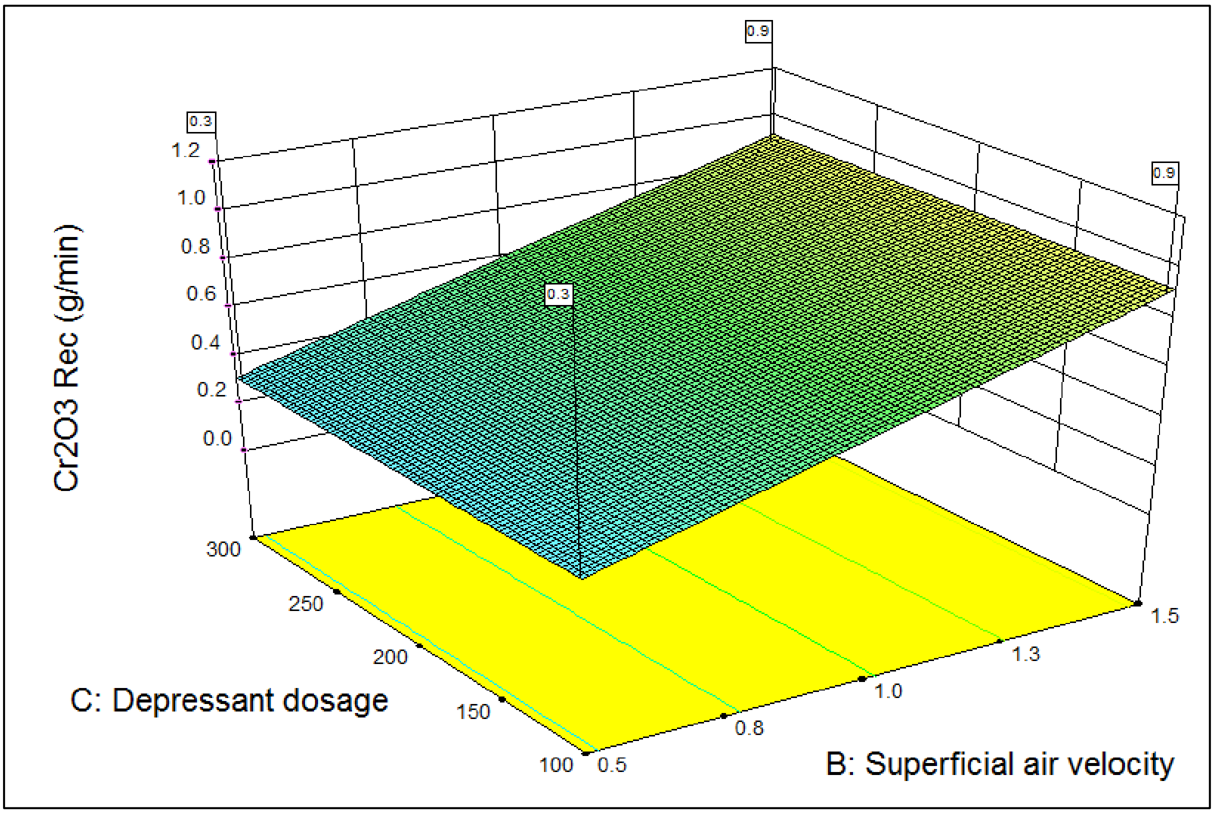


Figure 4.31 Effect of superficial air velocity and froth height on chrome recovery keeping other factors at base levels (24 cm froth height & 25 ppm frother)

4.5.3.3 *Effect of Superficial Air velocity and Frother Concentration on Chrome Recovery*

The effect of superficial air velocity and frother concentration on chrome recovery is given in Figure 4.32 keeping other factors at base level (200 g/t depressant and18 cm froth height). From Figure 4.32, it was observed that there was an increase in chrome recovery with increasing superficial air velocity both at high and low frother concentrations. The chrome recovery also increased with increasing frother concentration at low and high superficial air velocities. Similar observations were found with superficial air velocity and froth height keeping other factors at high and low levels (Appendix-D).

The results can be summarised as:

- Chrome recovery is directly proportional to the changes in superficial air velocity and frother concentration.
- Superficial air velocity had a greater effect on chrome recovery than frother concentration.

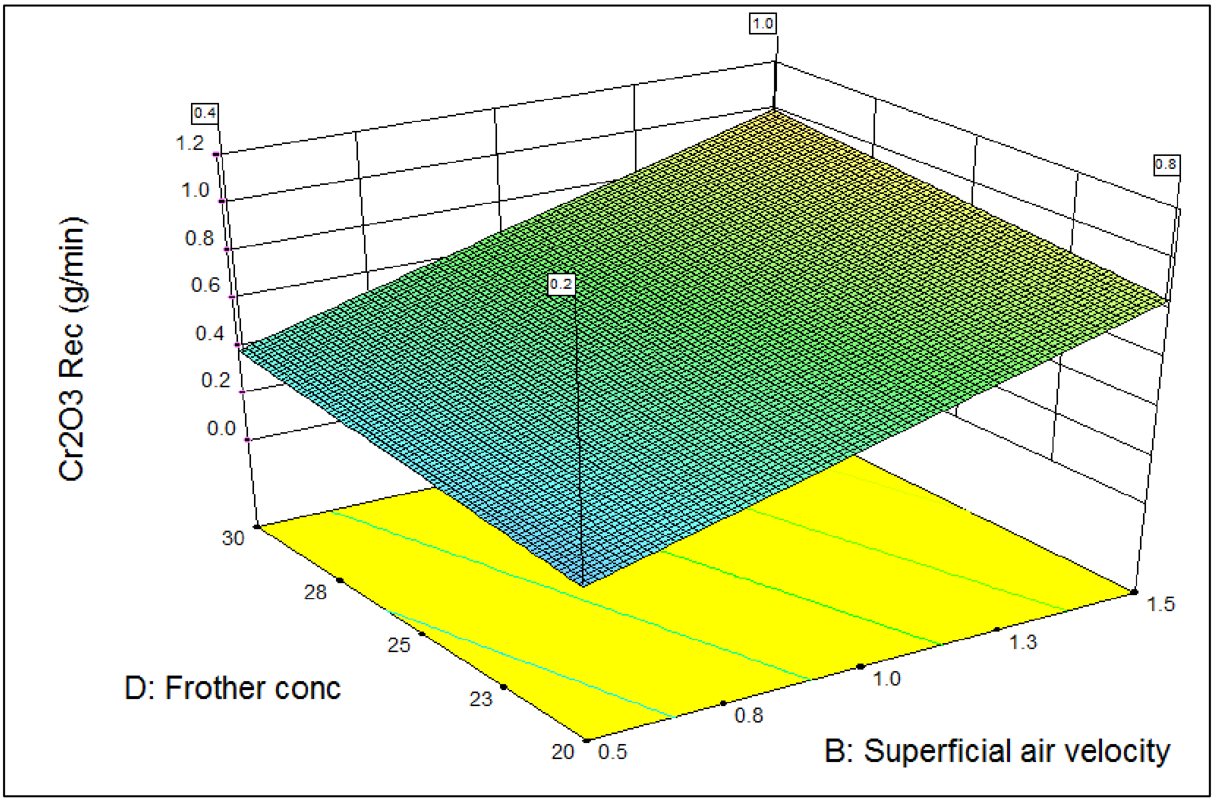


Figure 4.32 Effect of superficial air velocity and frother concentration on chrome recovery keeping other factors at base level (24 cm froth height & 200 g/t depressant)

4.5.3.4 Effect of Froth height and Depressant Dosage on Chrome Recovery

The effect of froth height and depressant dosage on chrome recovery was found to be similar in all the levels of other factors (low, base and high). The effect of froth height and depressant dosage is shown in Figure 4.33, keeping other factors at base level. From Figure 4.33, it is observed that chrome recovery decreased with increases in froth height both at high and low depressant dosage. While in the case of depressant dosage there was no change in chrome recovery with an increase in depressant dosage both at high and low froth height. Similar observations were found in case of other factors at low and high levels (Appendix-D).

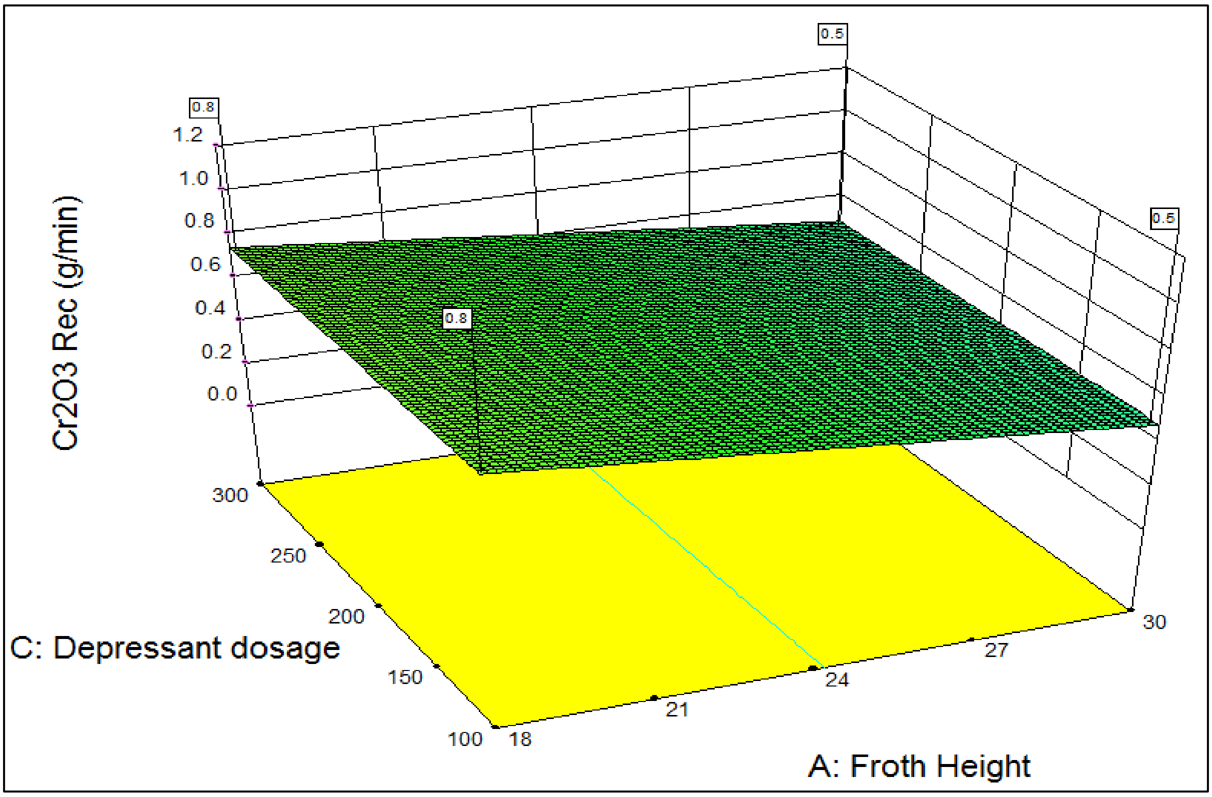


Figure 4.33 Effect of froth height and depressant dosage on chrome recovery keeping other factors at base level (1 cm/sec superficial air velocity & 25 ppm frother)

4.5.3.5 Effect of Froth height and Frother Concentration on Chrome Recovery

Figure 4.34 shows the effect of froth height and frother concentration on chrome recovery while keeping the other factors at base levels. The chrome recovery decreased with an increase in froth height both at high and low frother concentrations. There was a small increase in chrome recovery with an increase in frother concentration both at high and low froth heights. Similar observations were made at high and low levels of the other factors (Appendix-D).

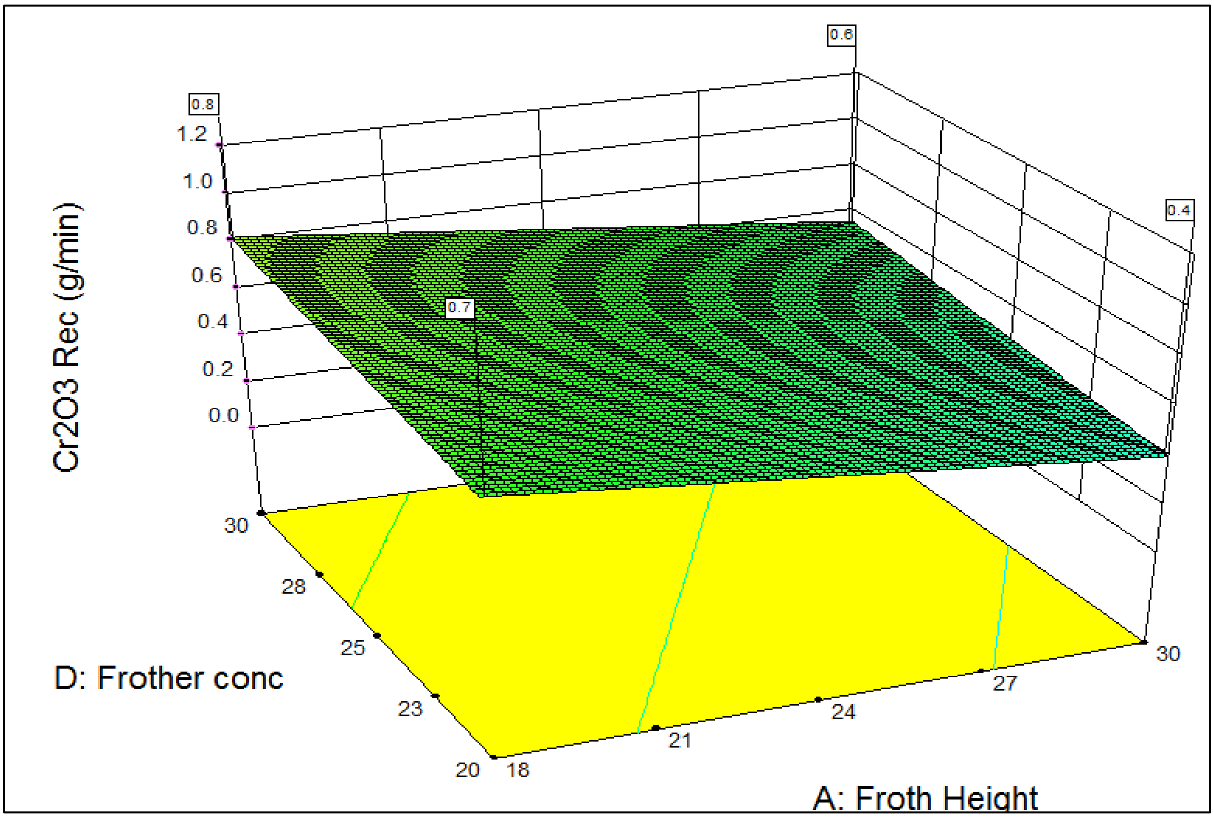


Figure 4.34 Effect of froth height and frother concentration on chrome recovery keeping other factors at base level (1 cm/sec superficial air velocity & 200 g/t depressant)

4.5.3.6 Effect of Depressant Dosage and Frother Concentration on Chrome Recovery

Figure 4.35 shows the effect of depressant dosage and frother concentration on chrome recovery while keeping the other factors at base levels (24 cm froth height and 1 cm/sec superficial air velocity). The recovery of chromite was directly proportional to the change in frother concentration and shows no effect with changes in depressant dosage. Similar observations also made in the case of low and high levels of the other factors (Appendix-D).

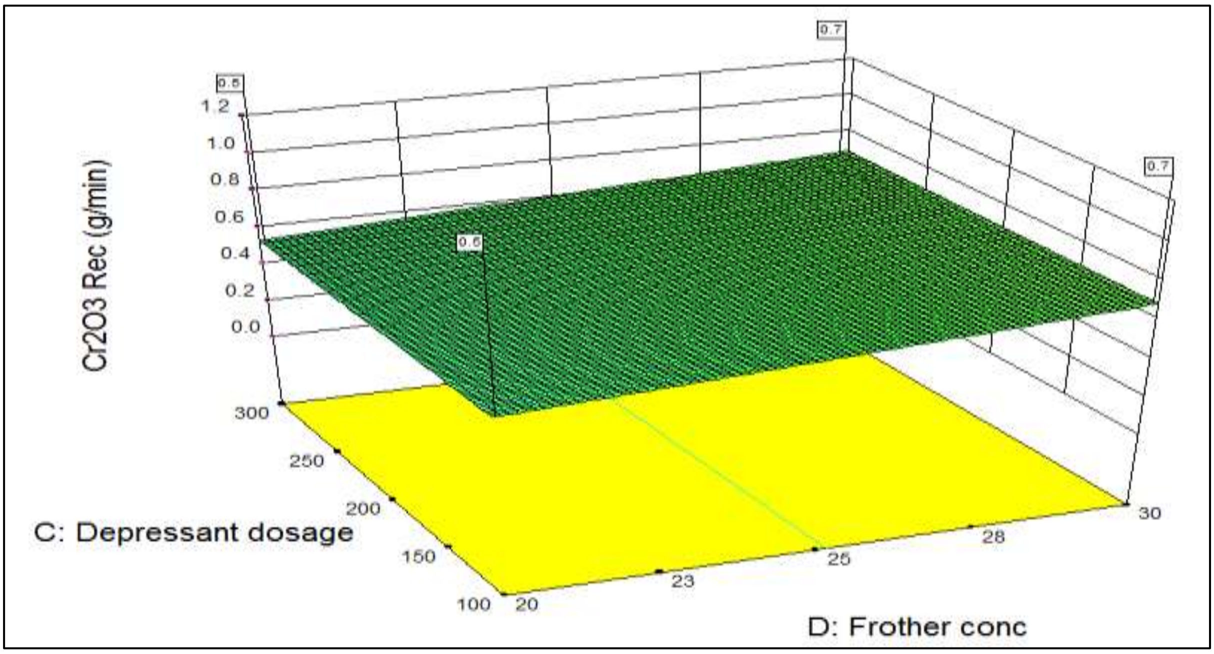


Figure 4.35 Effect of depressant dosage and frother concentration on chrome recovery keeping other factors at base level (1 cm/sec superficial air velocity & 24 cm of froth height)

4.5.4 Response of Chrome Grade to Process Parameters

The effect of various process parameters were studied for the response of chrome grade. The regression equation for the response is given in Equation 4.4.

$$\begin{aligned} Chrome\ Grade(\%) \\ &= 11.68 - 0.85 * FH + 1.30 * SAV + 1.96 * DD + 0.76 * FC + 0.45 * FH \\ &* DD - 1.19 * SAV * DD - 0.52 * SAV * FC - 0.67 * \ FH * SAV \\ &* DD \quad (4.4) \end{aligned}$$

The R^2 value for the equation was found to be 0.94 which can be considered as a good fit. All the factors have the significant effect on the chrome grade. There were found to be interactive effects among the four factors. The individual and interactive effect of factors and their percentage contributions to the response is given in Figure 4.36.

Figure 4.36 reveals that, except for froth height, all the factors had a positive effect on chrome grade. The contribution of depressant dosage (40%) is greater than any of the other process parameters. Froth height, superficial air velocity and frother concentration have contributions of 8%, 18% and 6%, respectively. Interactive effects among superficial air velocity and depressant dosage have a significant negative impact, with a contribution of 15%. Other interactive effects have a contribution of less than 5%.

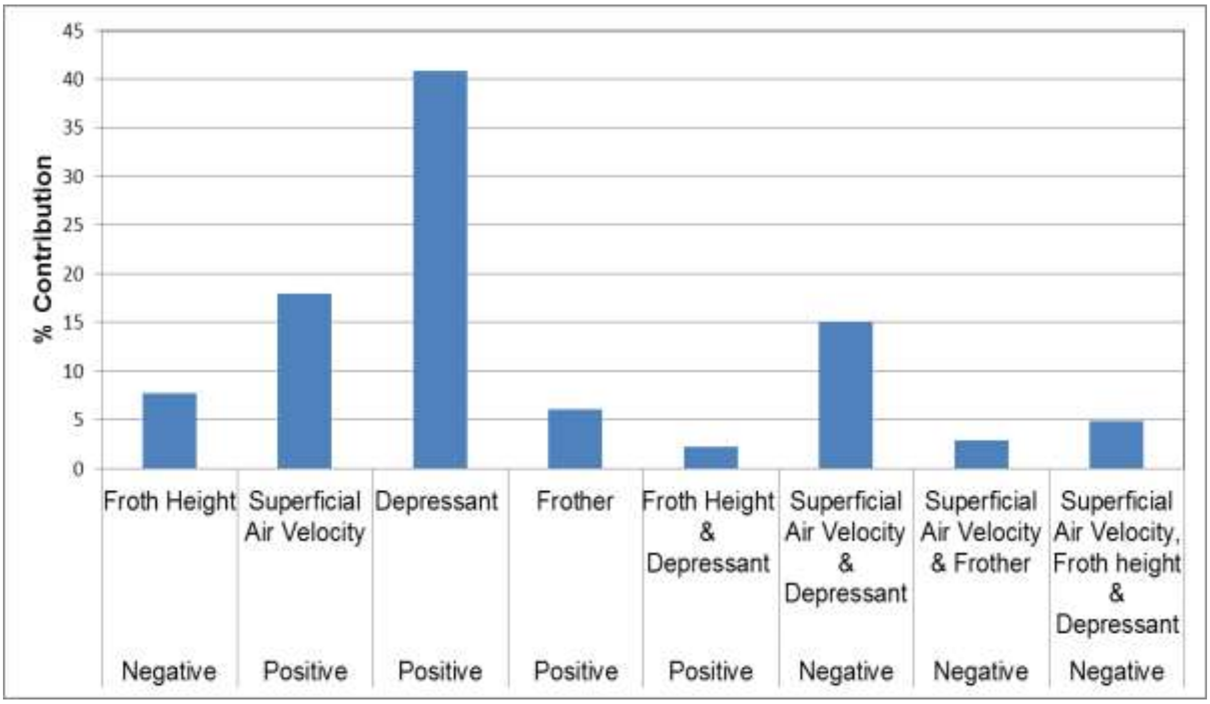


Figure 4.36 Effect of factors and their contribution to chrome grade

The order of percentage contribution of factors to chrome grade is as follows:

Depressant dosage> Superficial air velocity> Superficial air velocity and Depressant dosage > Froth height> Frother > Superficial air velocity, Froth height and Depressant dosage > Other interactions

4.5.4.1 Effect of Superficial Air velocity and Froth Height on Chrome Grade

The effect of superficial air velocity and froth height is given below in Figure 4.37, keeping the other two factors viz. depressant dosage and frother concentration at base levels (200 g/t depressant and 25 ppm frother). Figure 4.37 shows that an increase in superficial air velocity resulted in an increase in chrome grade both at high and low froth heights. In the case of froth height, an increase in froth height resulted in a decrease in chrome grade at high and low superficial air velocities. The superficial air velocity had a greater effect on chrome grade than froth height. Similar observations were made with respect to superficial air velocity and froth height with the other factors at high and low levels (Appendix-E).

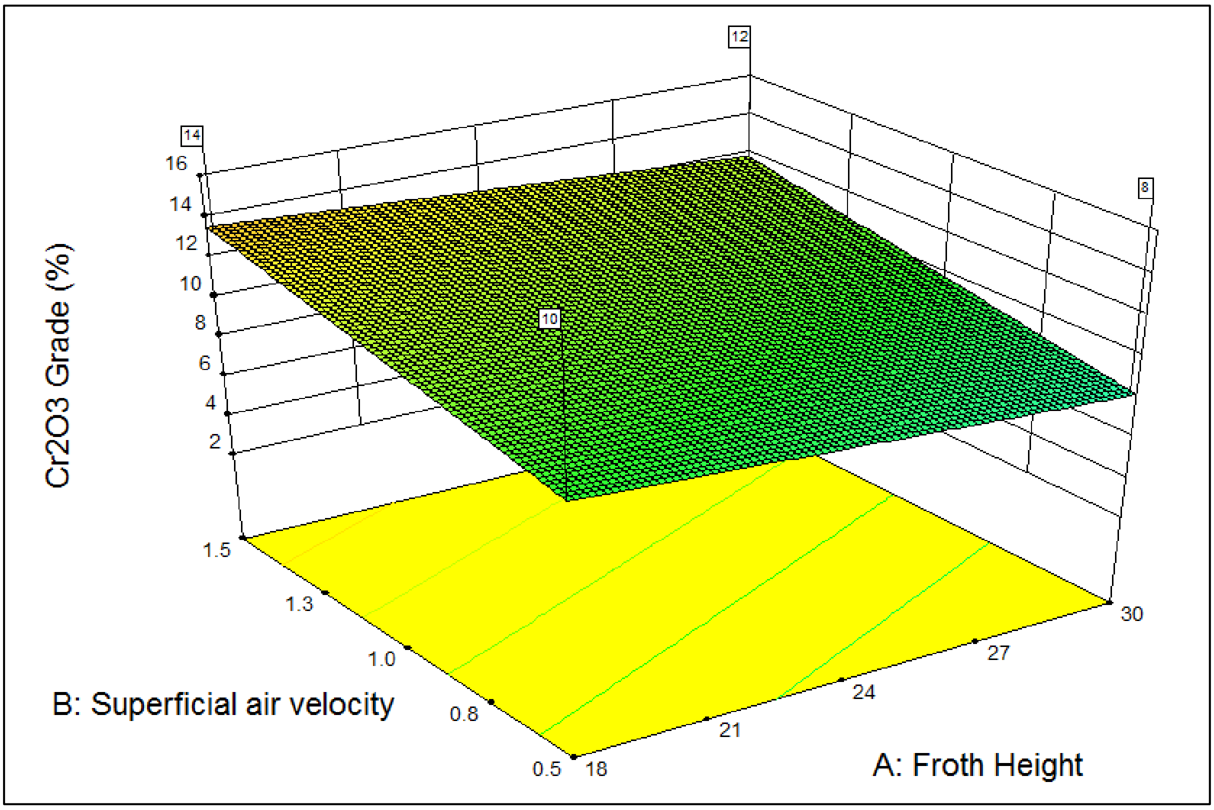


Figure 4.37 Effect of superficial air velocity and froth height on chrome grade keeping other factors at base levels (200 g/t depressant & 25 ppm frother)

4.5.4.2 Effect of Superficial Air velocity and Depressant Dosage on Chrome Grade

The effect of superficial air velocity and depressant dosage on chrome grade is shown in Figure 4.38. The chrome grade increased with an increase in superficial air velocity at both high and low depressant dosages. However, the increase is far greater at low depressant dosages than at high dosages. In the case of depressant dosage, there was a greater increase in chrome grade with increasing superficial air velocity at low dosages than at high dosages. Similar observations were made for the other factors at high and low levels (Appendix-E).

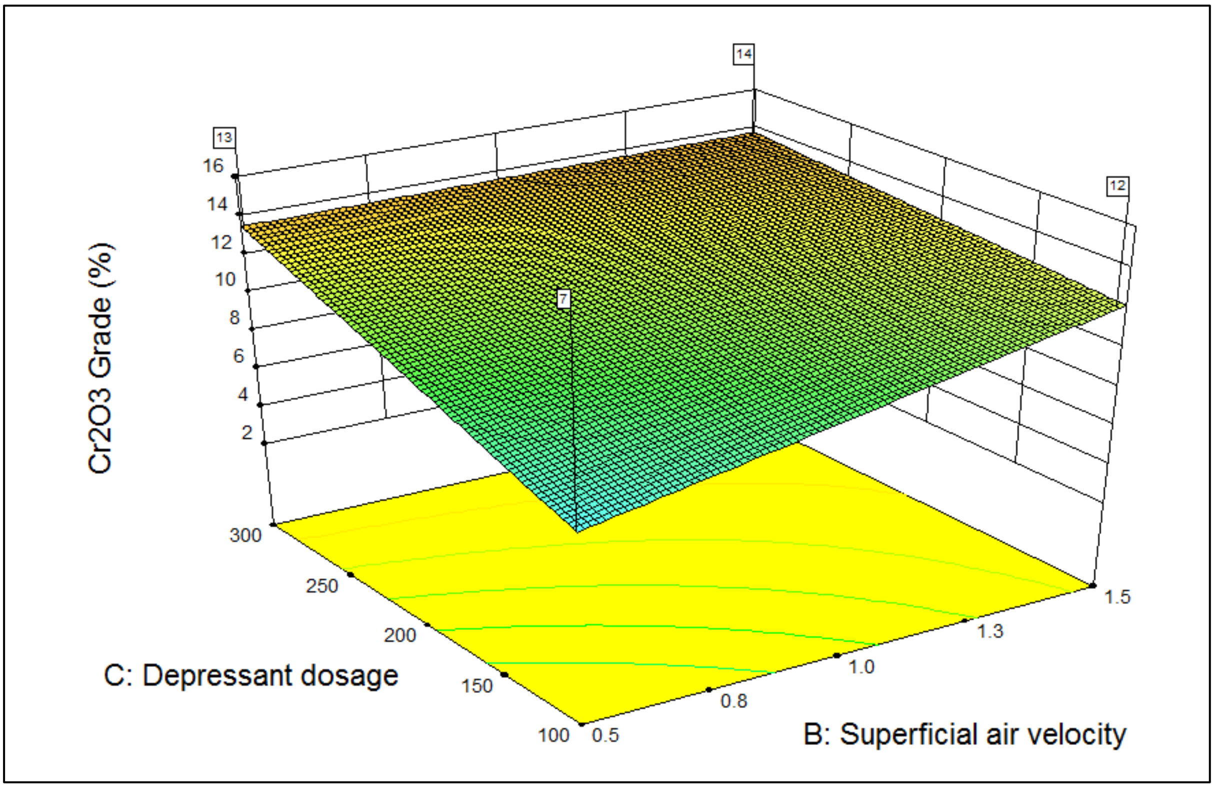


Figure 4.38 Effect of superficial air velocity and depressant dosage on chrome grade keeping other factors at base levels (1 cm/sec superficial air velocity and 200 g/t depressant dosage)

4.5.4.3 Effect of Superficial Air velocity and Frother Concentration on Chrome Grade

The effect of superficial air velocity and frother concentration on chrome grade is given in Figure 4.39 while keeping other factors at base level. Figure 4.39 shows that there was an increase in chrome grade with increasing superficial air velocity both at high and low frother concentrations but the increase was far greater at low frother concentrations. In the case of frother concentration, the chrome grade increased with increasing frother concentration at low superficial air velocity and there was no change at high superficial air velocity. Similar observations were made in the case of low and high levels of the other factors (Appendix-E).

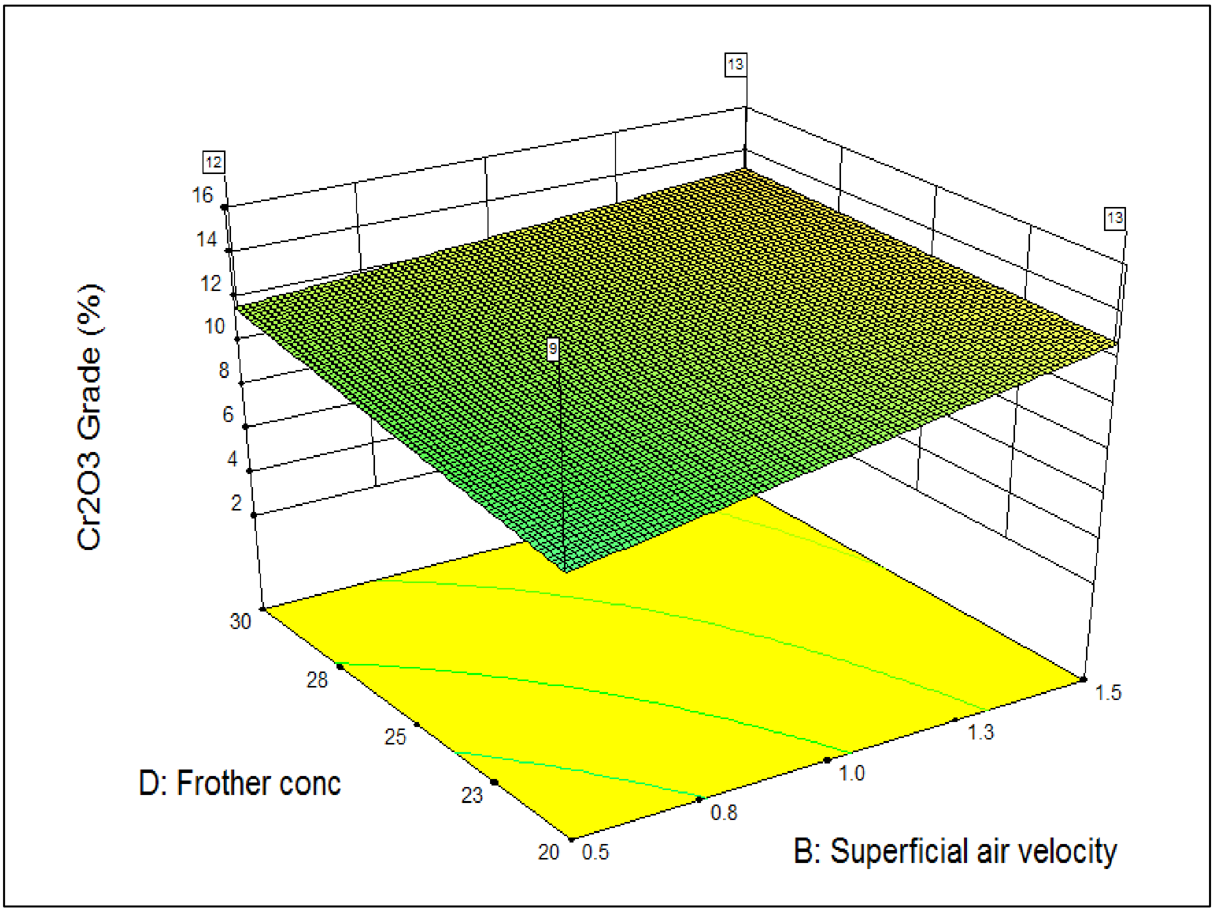


Figure 4.39 Effect of superficial air velocity and frother concentration on chrome grade keeping other factors at base level (200 g/t depressant and 25 ppm frother)

4.5.4.4 Effect of Froth Height and Depressant Dosage on Chrome Grade

The effect of froth height and depressant dosage was studied for chrome grade keeping the other factors at low base and high level. Figure 4.40 shows that chrome grade increased with increases in depressant dosage both at high and low froth heights. However, the increase was greater at high froth heights. An increase in froth height produced a decrease in chrome grade, more so at the low depressant dosages. Similar observations were found in the case of the other factors at low and high levels (Appendix-E).

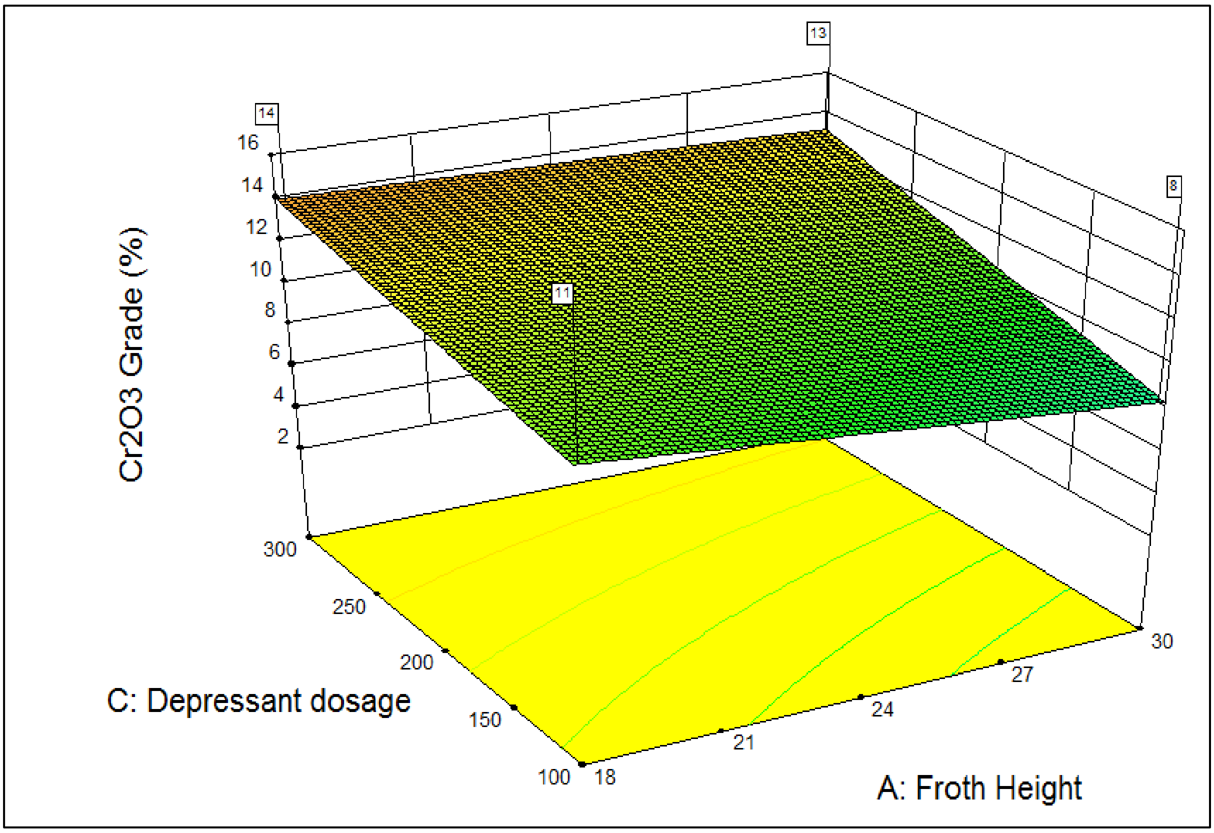


Figure 4.40 Effect of froth height and depressant dosage on chrome grade keeping other factors at base level (1 cm/sec superficial air velocity & 25 ppm frother)

4.5.4.5 Effect of Froth Height and Frother Concentration on Chrome Grade

The effect of froth height and frother concentration, while keeping the other factors at low base and high level, are shown in Figure 4.41. The chrome grade decreased with an increase in froth height both at high and low frother concentrations and increased with an increase in frother concentration at high and low froth heights. The effects were found to be similar for the response of chrome grade at all levels of other factors (Appendix-E).

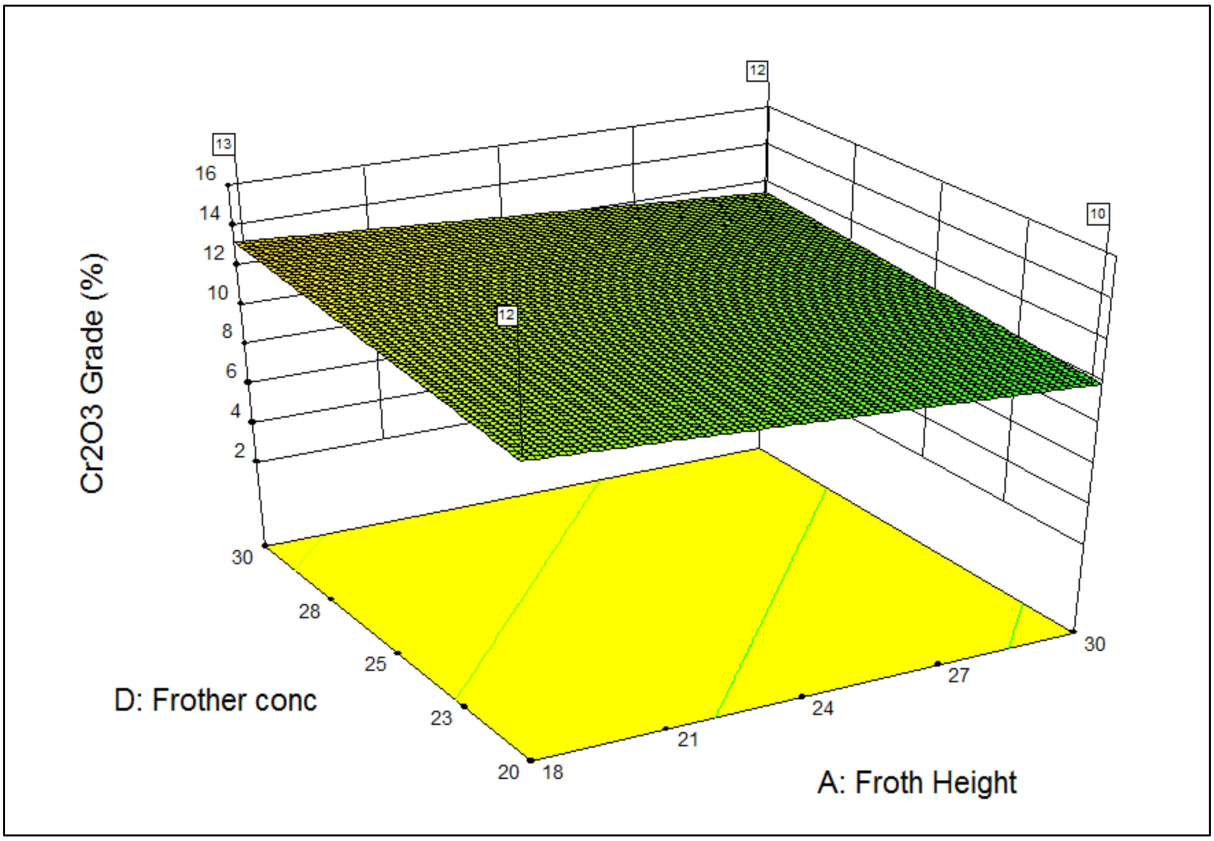


Figure 4.41 Effect of froth height and frother concentration on chrome grade keeping other factors at base level (1 cm/sec superficial air velocity & 200 g/t depressant)

4.5.4.6 Effect of Depressant Dosage and Frother Concentration on Chrome Grade

The effect of depressant dosage and frother concentration, at base levels of the other factors, is shown in Figure 4.42. The chrome grade increased by a small amount with an increase in frother concentration. Similarly, the chrome grade increased with an increase in depressant dosage. However, the depressant dosage was the overriding effect. Similar effects were also found for the response of chrome grade at all levels of other factors (Appendix-E).

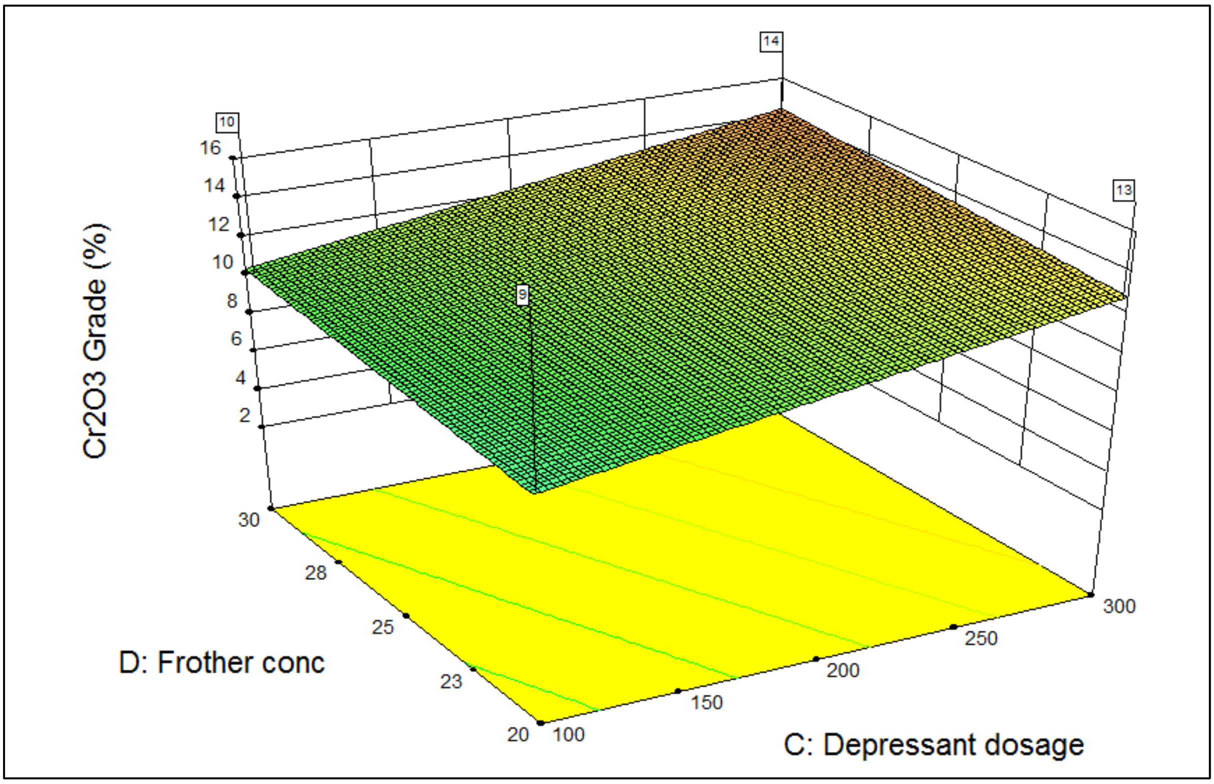


Figure 4.42 Effect of depressant dosage and frother concentration on chrome grade keeping other factors at base level (1 cm/sec superficial air velocity & 24 cm of froth height)

4.5.5 Response of PGM Recovery to Process Parameters

The regression equation for the PGM recovery after discarding the insignificant factors is given in Equation 4.4.5.

$$PGM\ Rec\ (\%) = 69.21 - 0.86 * FH + 1.16 * SAV - 0.55 * SAV * DD - 0.31 * FH * DD * FC \qquad (4.5)$$

The individual and interactive effects of the factors and their contribution to PGM recovery is given in Figure 4.43. From an observation of Figure 4.44, it appears that the superficial air velocity had a positive effect on PGM recovery and the contribution was significant compared to the other process parameters. The second most dominant factor was the negative contribution of froth height. The individual effect of depressant dosage had no effect on PGM recovery while there were interaction effects which included superficial air velocity, froth height, depressant and frother concentration.

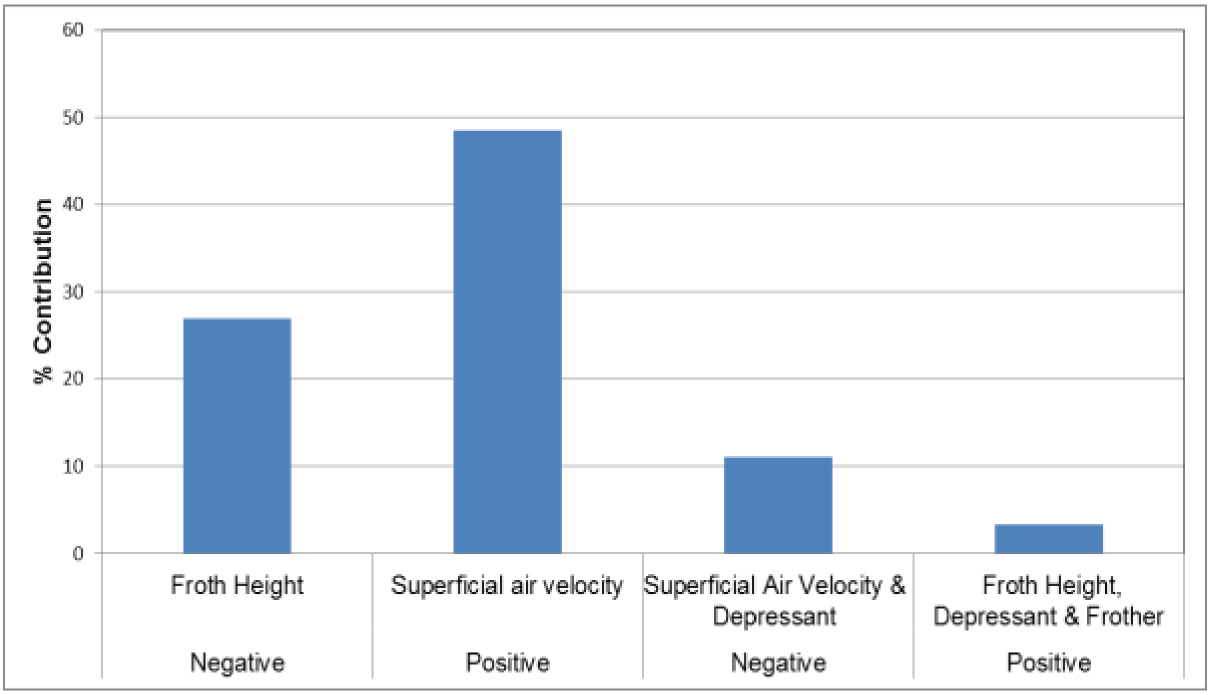


Figure 4.43 Effect of factors and their contribution on PGM recovery

The order of contribution of factors for PGM recovery was as follows

Superficial air velocity>Froth height> Superficial air velocity and Depressant dosage> Froth height, Depressant dosage and Frother concentration.

4.5.5.1 *Effect of Superficial Air velocity and Froth Height on PGM Recovery*

The effect of superficial air velocity and froth height on PGM recovery is shown in Figure 4.44. These effects were found to be similar at all levels of other factors (Appendix-F).

The PGM recovery increased with an increase in superficial air velocity both at high and low froth heights. In the case of froth height, PGM recovery increased with a decrease in froth height at high and low superficial air velocities.

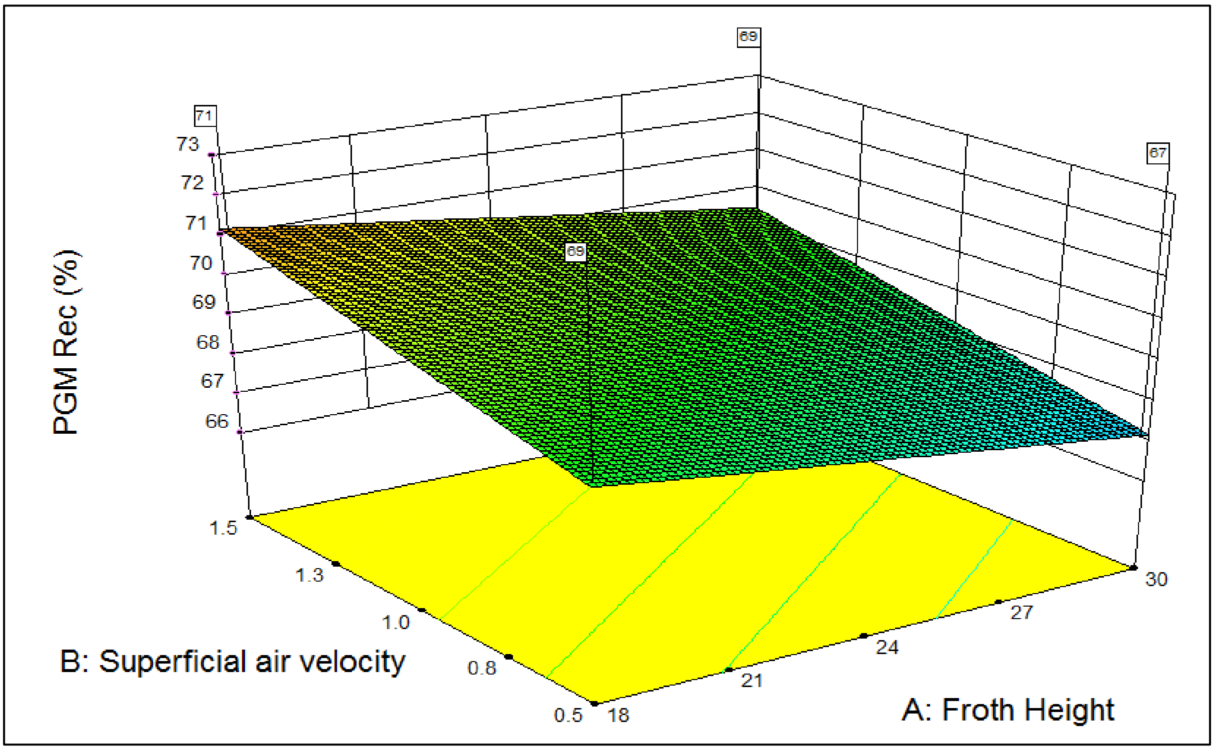


Figure 4.44 Effect of superficial air velocity and froth height on PGM recovery keeping other factors at low level (25 ppm frother & 200 g/t depressant)

4.5.5.2 *Effect of Superficial Air velocity and Depressant Dosage on PGM Recovery*

PGM recovery changed as a function of superficial air velocity and depressant dosage. This is shown in Figure 4.45. PGM recovery increased with an increase in superficial air velocity both at high and low depressant dosage, but more so at low depressant dosages. At low superficial air velocity there was no change in PGM recoveries with an increase in depressant dosage. However, at high superficial air velocity there was a decrease in PGM recovery with an increase in depressant dosage. As the levels of the other factors (froth height and frother concentration) are varied, the response of depressant dosage varies slightly, but changes in PGM recoveries are small (Appendix-F).

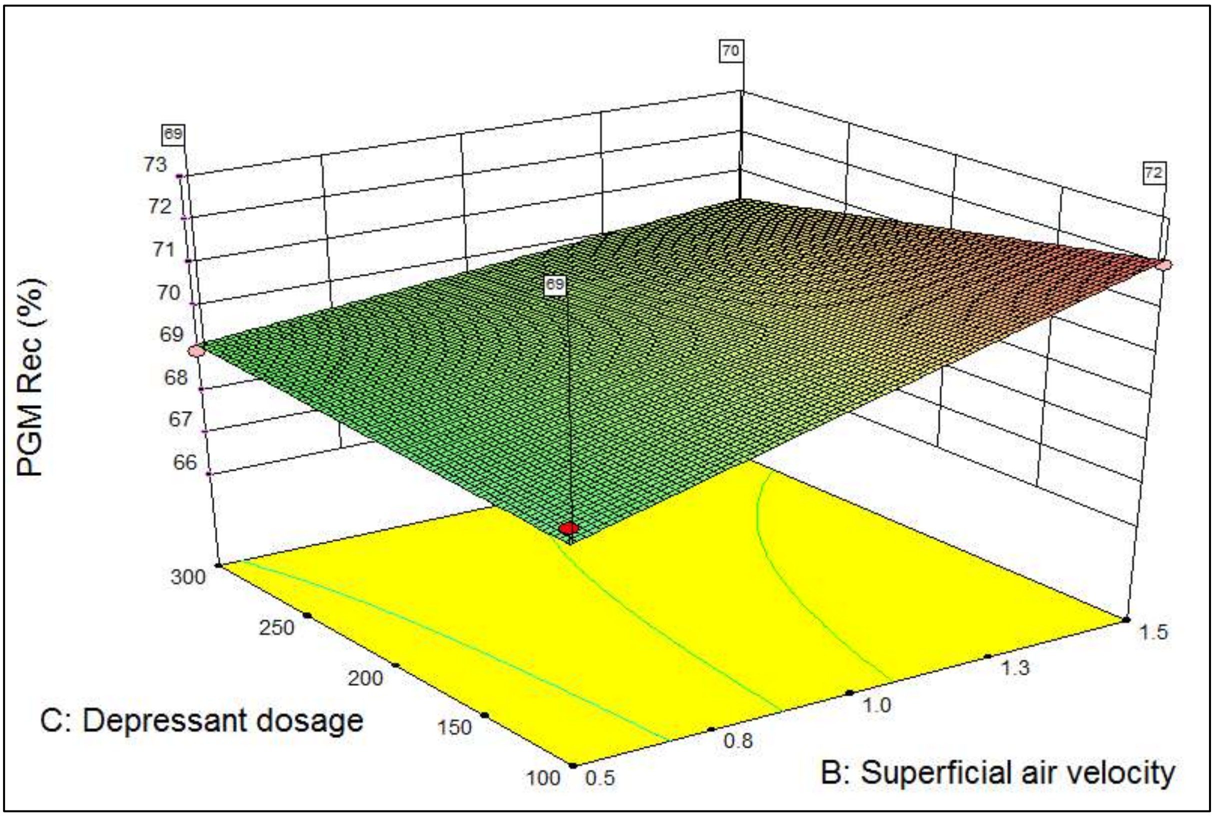


Figure 4.45 Effect of superficial air velocity and depressant dosage on PGM recovery keeping other factors at low level (20 ppm frother & 18 cm froth height)

4.5.5.3 *Effect of Superficial Air velocity and Frother Concentration on PGM Recovery*

Figure 4.46 shows PGM recovery as a function of superficial air velocity and frother concentration. There was an increase in PGM recovery observed with increasing superficial air velocity both at high and low frother concentrations. Frother concentration had no effect on the PGM recovery.

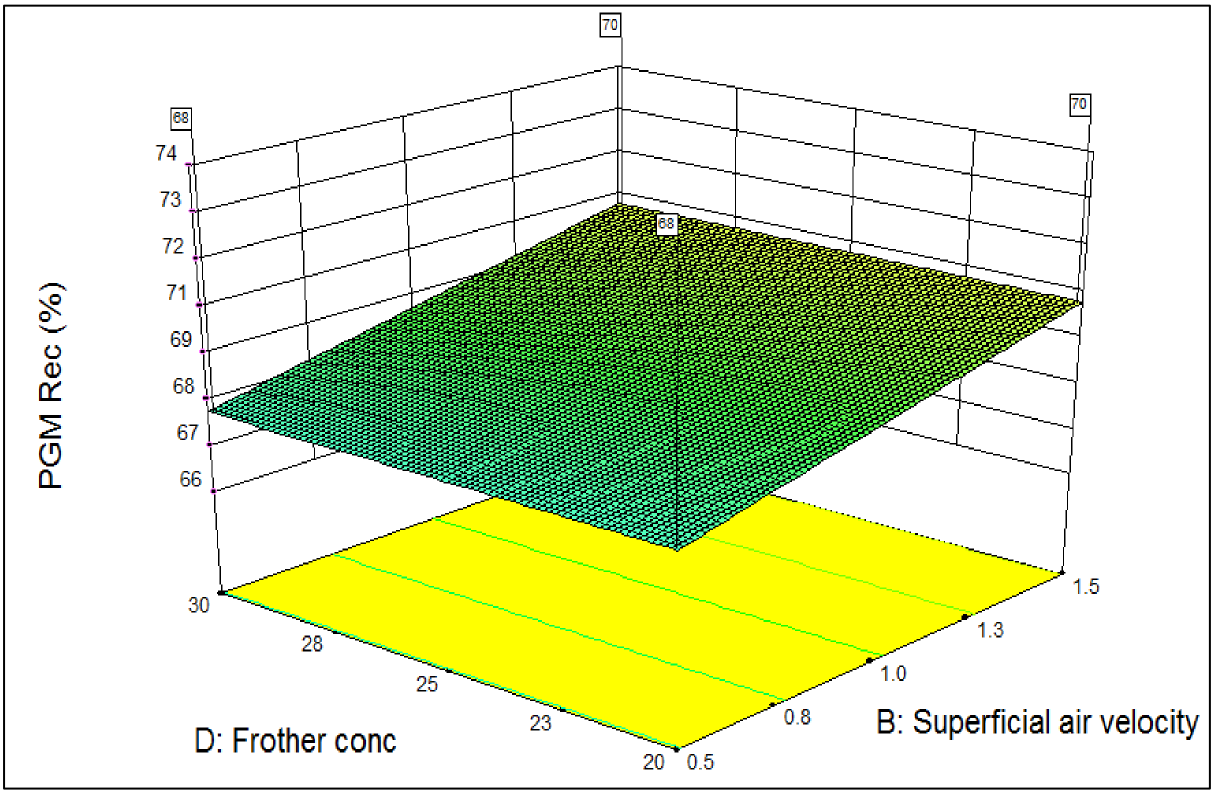


Figure 4.46 Effect of superficial air velocity and frother concentration on PGM recovery keeping other factors at base level (200 g/t depressant and 25 ppm frother)

4.5.5.4 Effect of Froth Height and Depressant Dosage on PGM Recovery

The effect of froth height and depressant dosage on PGM recovery is shown in Figure 4.47. PGM recovery decreased with an increase in froth height at low and high depressant dosages. Depressant dosage had no effect on the PGM recovery. Similar effects found in other levels (Appendix-F).

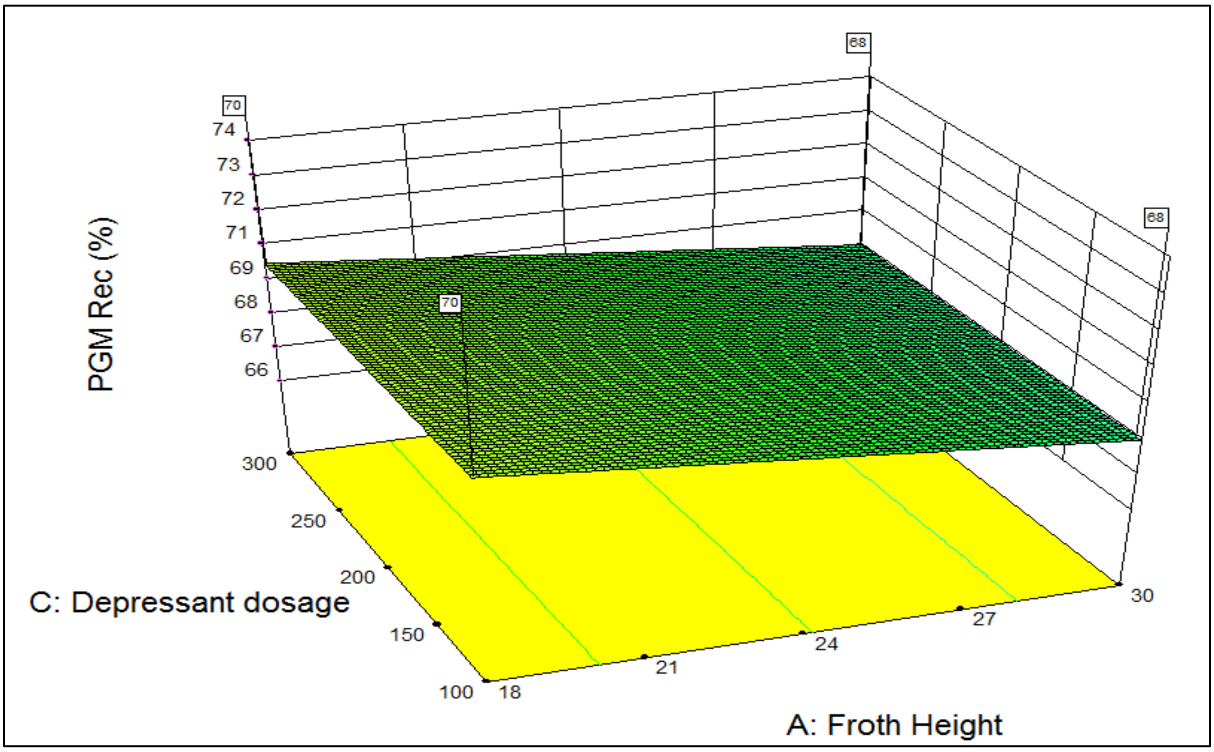


Figure 4.47 Effect of froth height and depressant dosage on PGM recovery keeping other factors at base level (1 cm/sec superficial air velocity & 25 ppm frother)

4.5.5.5 Effect of Froth Height and Depressant Frother Concentration on PGM Recovery

Figure 4.48 shows PGM recovery as a function of froth height and frother concentration. Frother concentration had no effect on PGM recovery, while there was a decrease in PGM recovery with an increase in froth height at both low and high frother concentrations. Similar observation found at low and high levels (Appendix-F)

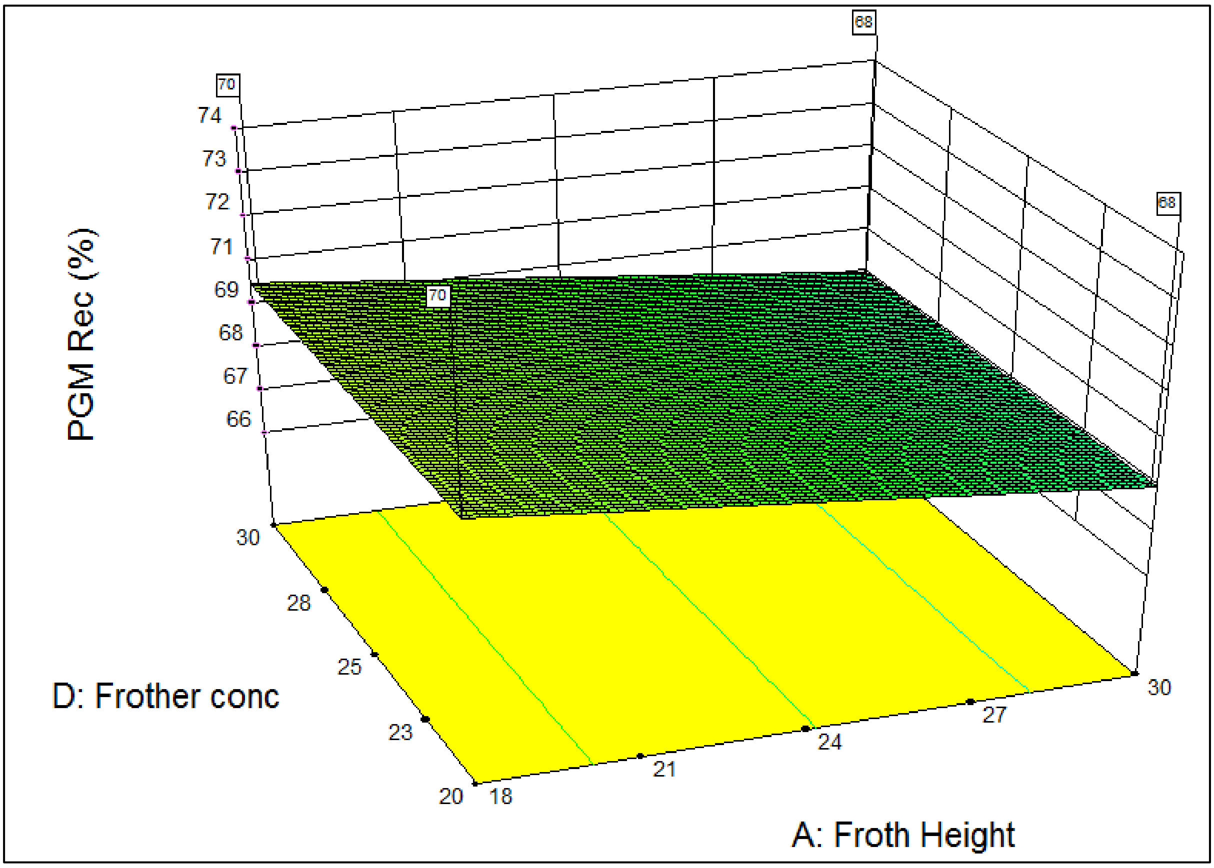


Figure 4.48 Effect of froth height and frother concentration on PGM recovery keeping other factors at low level (1 cm/sec superficial air velocity & 200 g/t depressant)

4.5.5.6 Effect of Depressant Dosage Frother Concentration on PGM Recovery

Figure 4.49 shows the effect of depressant dosage and frother concentration on PGM recovery. This shows that neither depressant dosage, nor frother concentration had any effect on the PGM recovery.

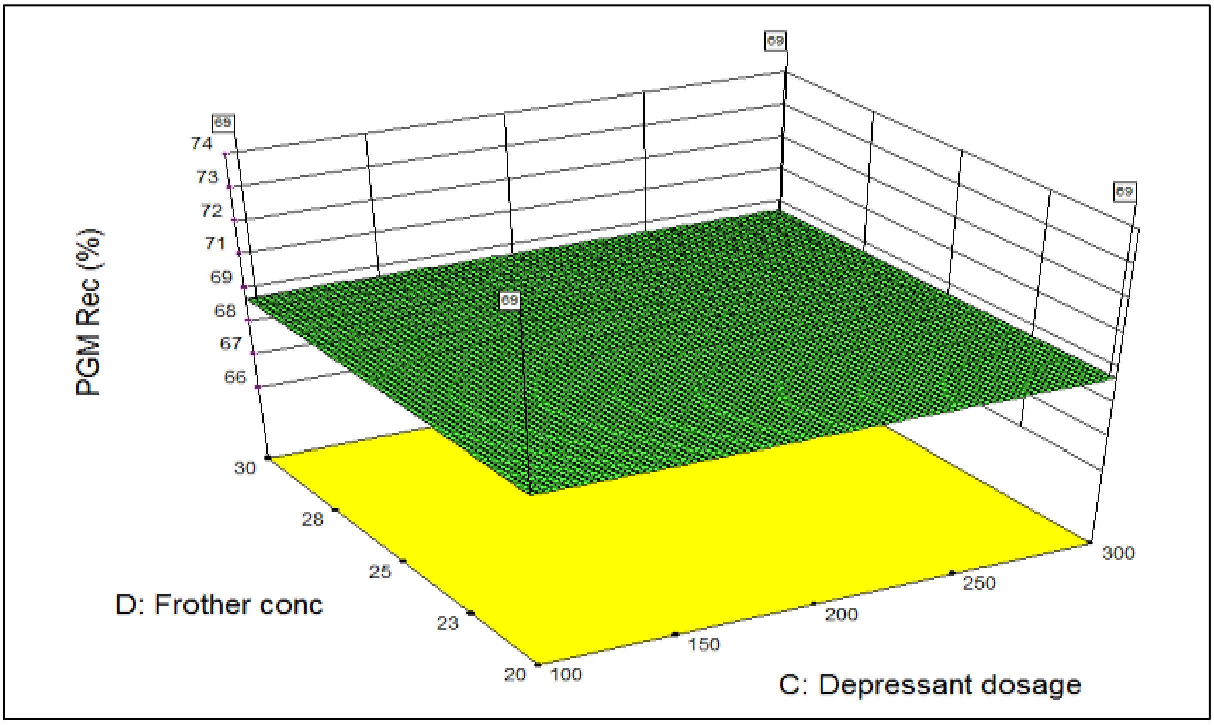


Figure 4.49 Effect of depressant dosage and frother concentration on PGM recovery keeping other factors at base level (1 cm/sec superficial air velocity & 24 cm froth height)

4.5.6 Response of PGM Grade to Process Parameters

The response of PGM grade was studied for the four factors and the effects of the factors is expressed by the regression equation given in equation 4.6. For the PGM grade the ratio of maximum to minimum response was found close to 10. So logarithmic response transform was chosen for better prediction of the model.

$$Ln\left(PGM\ grade\left(\frac{g}{t}\right)\right) = 4.66 + 0.29FH - 0.36SAV + 0.26SAV * FC \qquad (4.6)$$

The individual and interactive effects of factors and their contribution to PGM grade is given in Figure 4.50. From Figure 4.50, it appears that the superficial air velocity had a negative effect on PGM recovery and the contribution was greater than the other process parameters. The second most dominant factor was froth height and it had a positive contribution. The individual effects of depressant dosage and frother concentration had no effect on PGM grade, while there was an interactive effect observed between superficial air velocity and frother concentration.

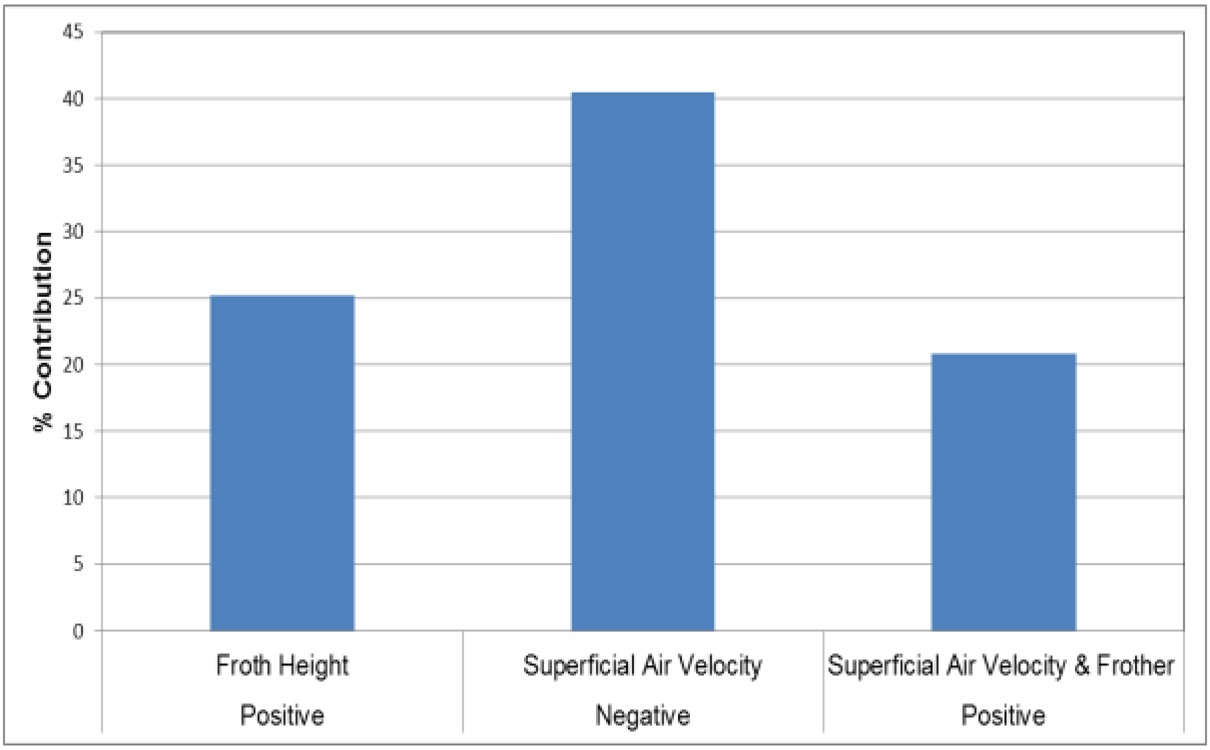


Figure 4.50 Effect of factors and their contribution to PGM grade

The order of percentage contribution of factors for PGM grade is as follows:

Superficial air velocity>Froth height> Superficial air velocity and frother

4.5.6.1 *Effect of Superficial Air velocity and Froth Height on PGM Grade*

The effect of superficial air velocity and froth height on PGM grade is shown in Figure 4.51. PGM grade increased with a decrease in superficial air velocity at high and low froth heights (18 and 30 cm). The increase was greatest at the highest froth heights. Conversely, PGM grade increased with an increase in froth height at high and low superficial air velocities. However, the increase in grade was greater at low air flow rates. The effects of superficial air velocity and froth height were found to be similar at all levels of the other parameters (Appendix-G)

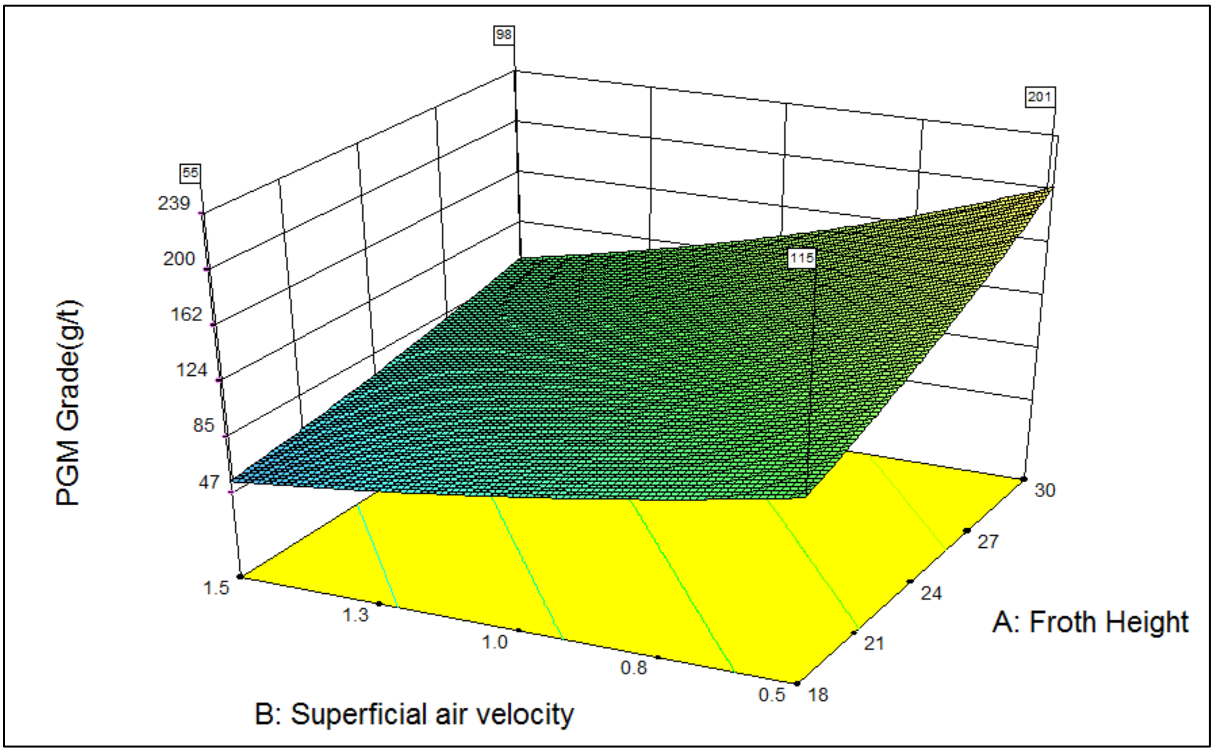


Figure 4.51 Effect of superficial air velocity and froth height on PGM grade keeping other factors at low level (25 ppm frother & 200 g/t depressant)

4.5.6.2 Effect of Superficial Air velocity and Depressant Dosage on PGM Grade

The response of PGM grade to superficial air velocity and depressant dosage is shown in Figure 4.51 (keeping other factors at base levels i.e. 24 cm froth height and 25 ppm frother concentration). PGM grade is shown to be inversely proportional to the superficial air velocity at low and high depressant dosage. While in the case of depressant dosage, there was no effect of depressant dosage on PGM grade at high and low superficial air velocities. Similar observations were made at high and low levels of the other factors.

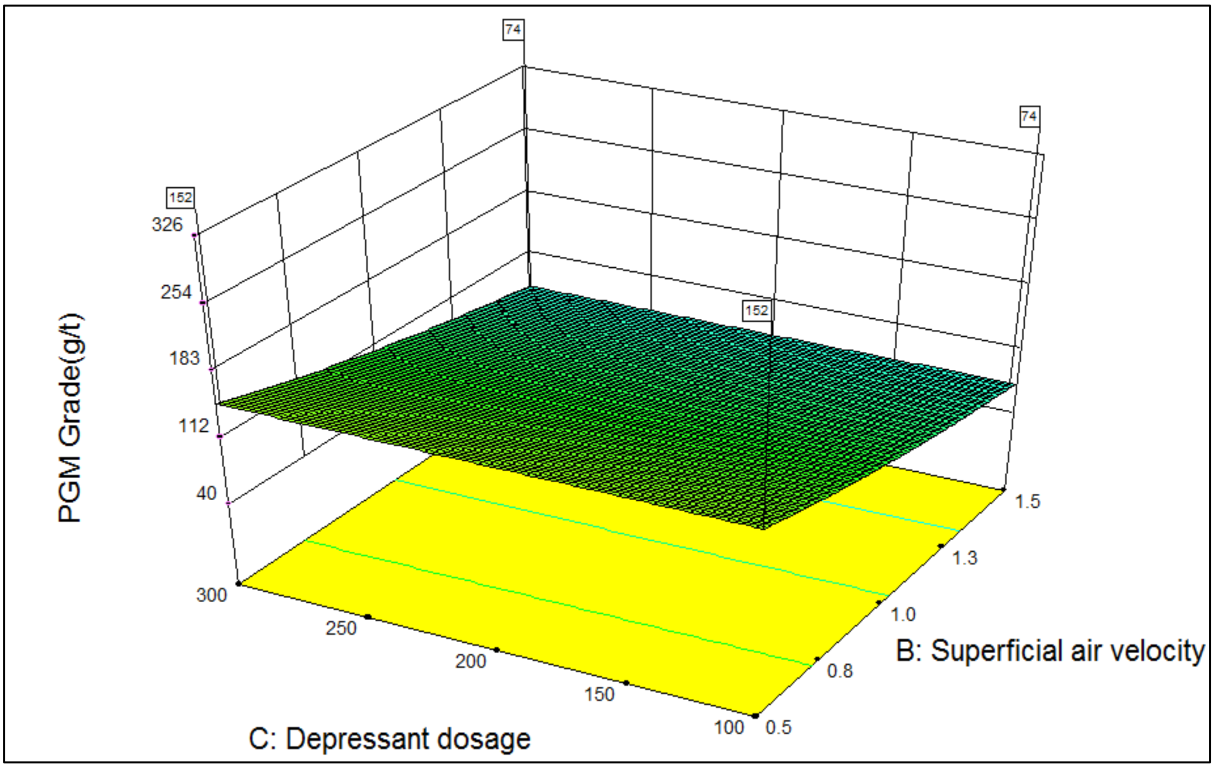


Figure 4.52 Effect of superficial air velocity and depressant dosage on PGM grade keeping other factors at low level (25 ppm frother & 18 cm froth height)

4.5.6.3 *Effect of Superficial Air velocity and Frother Concentration on PGM Grade*

The effect of superficial air velocity and frother concentration on PGM grade is shown in Figure 4.53 (keeping other factors at base levels i.e. 24 cm froth height and 200 g/t depressant dosage). PGM grade is shown to be inversely proportional to the superficial air velocity at low and high frother concentration. The rate of change is higher at low frother concentrations. As the frother concentration was increased, the PGM grade decreased at low air rates. However, at high air rates, the PGM grade increased with an increase in frother concentration.

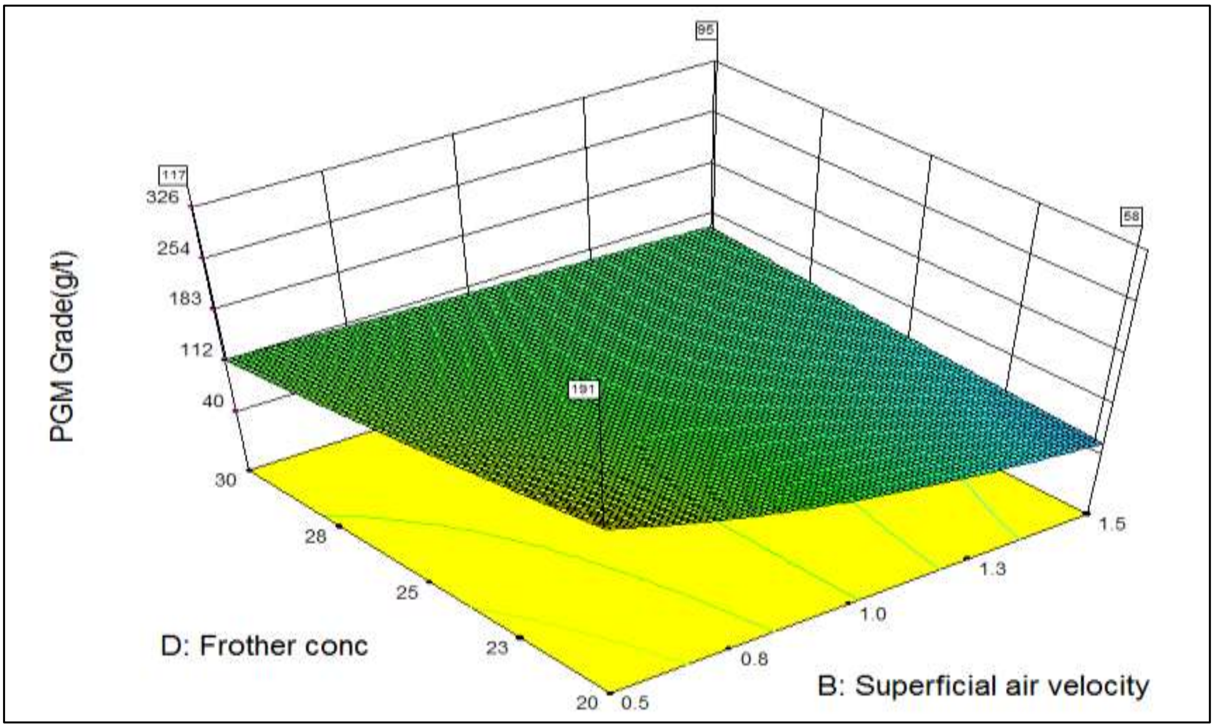


Figure 4.53 Effect of superficial air velocity and frother concentration on PGM grade keeping other factors at base level (300 g/t depressant dosage & 18 cm froth height)

4.5.6.4 Effect of Froth Height and Depressant Dosage on PGM Grade

The effect of froth height and depressant dosage on PGM grade is shown in Figure 4.54. PGM grade increased with an increase in froth height at low and high depressant dosage. While in the case of depressant dosage, there was almost no change in PGM grade with a change in depressant dosage.

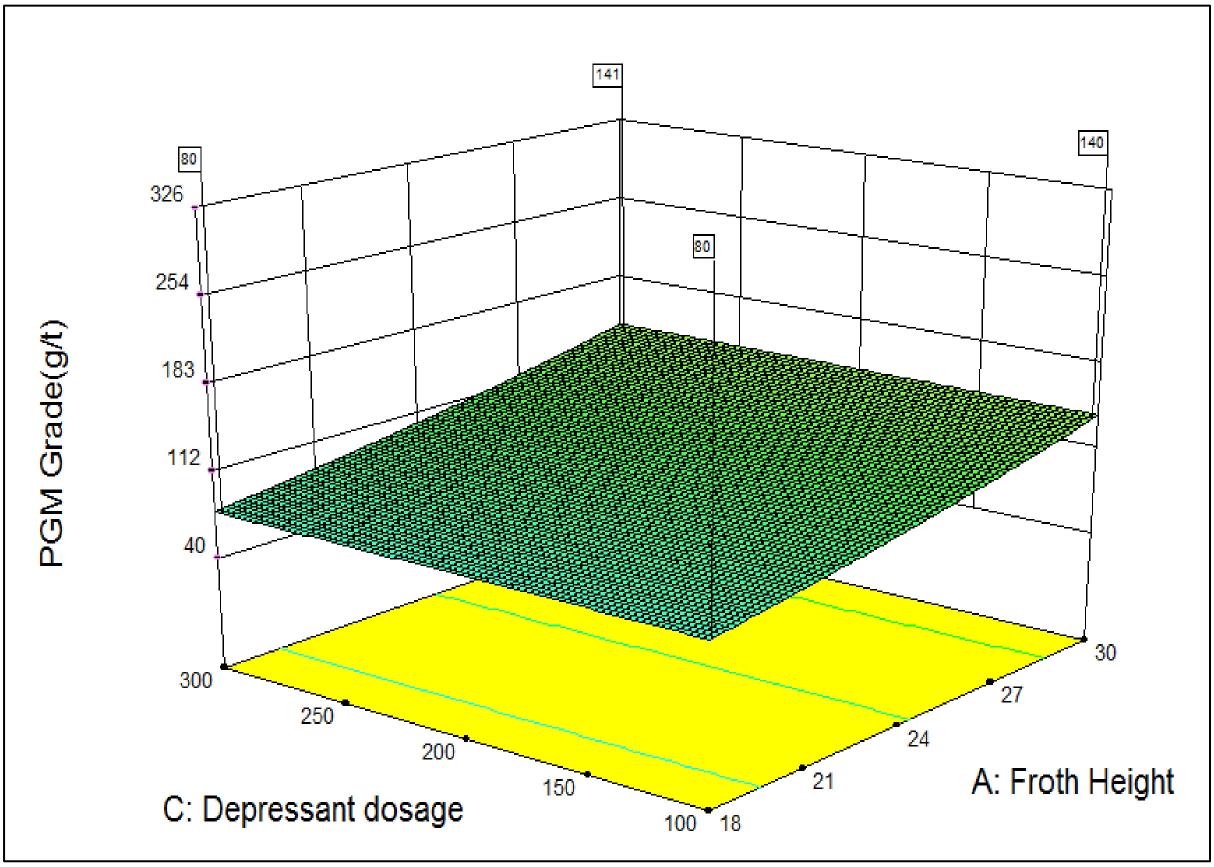


Figure 4.54 Effect of superficial froth height and depressant dosage on PGM grade keeping other factors at base level (1 cm/sec superficial air velocity & 25 ppm frother concentration)

4.5.6.5 Effect of Froth Height and Frother Concentration on PGM Grade

The dependence of PGM grade on froth height and frother concentration is shown in Figures 4.57, 4.58 and 4.59. From the figures it is evident that froth height has a similar effect on PGM grade in that the grade increased as the froth height increased. However, PGM grade may increase, decrease or remain the same, depending on the level of the other factors (superficial air velocity and depressant dosage).

At low levels of air flow and depressant dosage the PGM grade decreased as frother concentration increased at both high and low froth heights (Figure 4.57). The decrease was greater at high froth heights. At intermediate levels of superficial air velocity and depressant dosage the PGM grade remained virtually unchanged as the frother concentration increased (Figure 4.58). At high levels of air flow and depressant dosage the PGM grade increased slightly with increasing frother concentrations (Figure 4.59). However, all grades were relatively low under these conditions. These results are summarized in Table 4.13

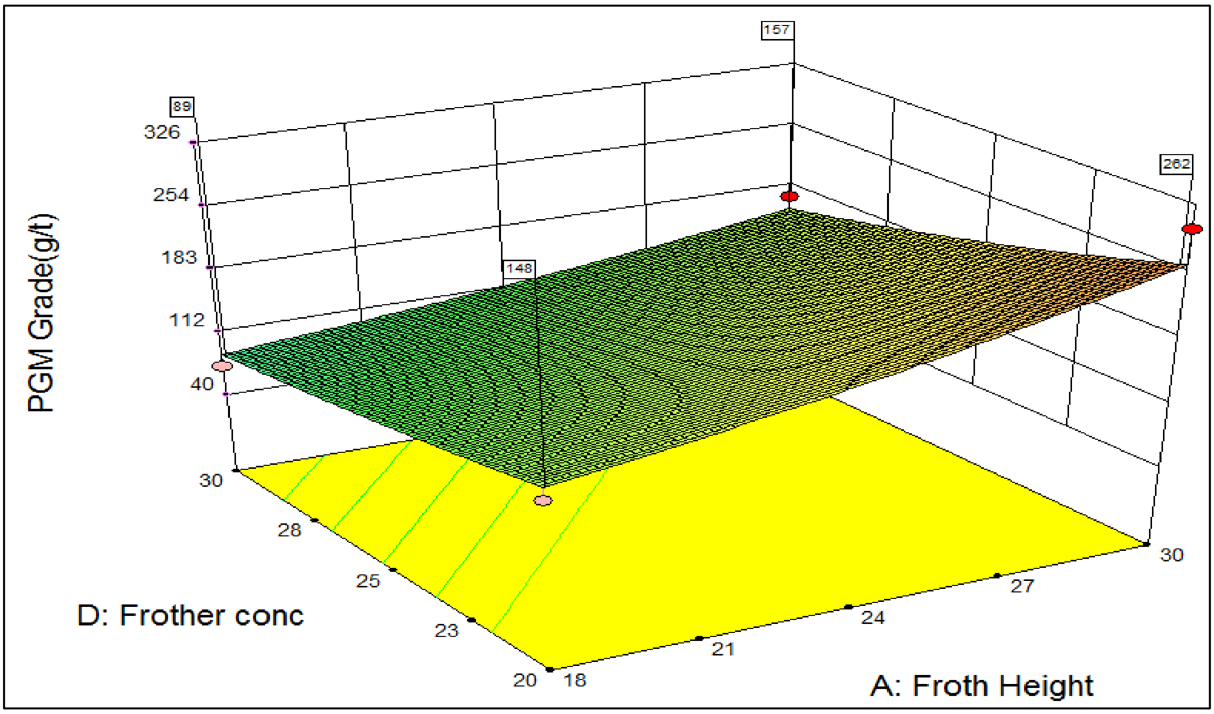


Figure 4.55 Effect of froth height and frother concentration on PGM grade keeping other factors at low level (0.5 cm/sec superficial air velocity & 100 g/t depressant dosage)

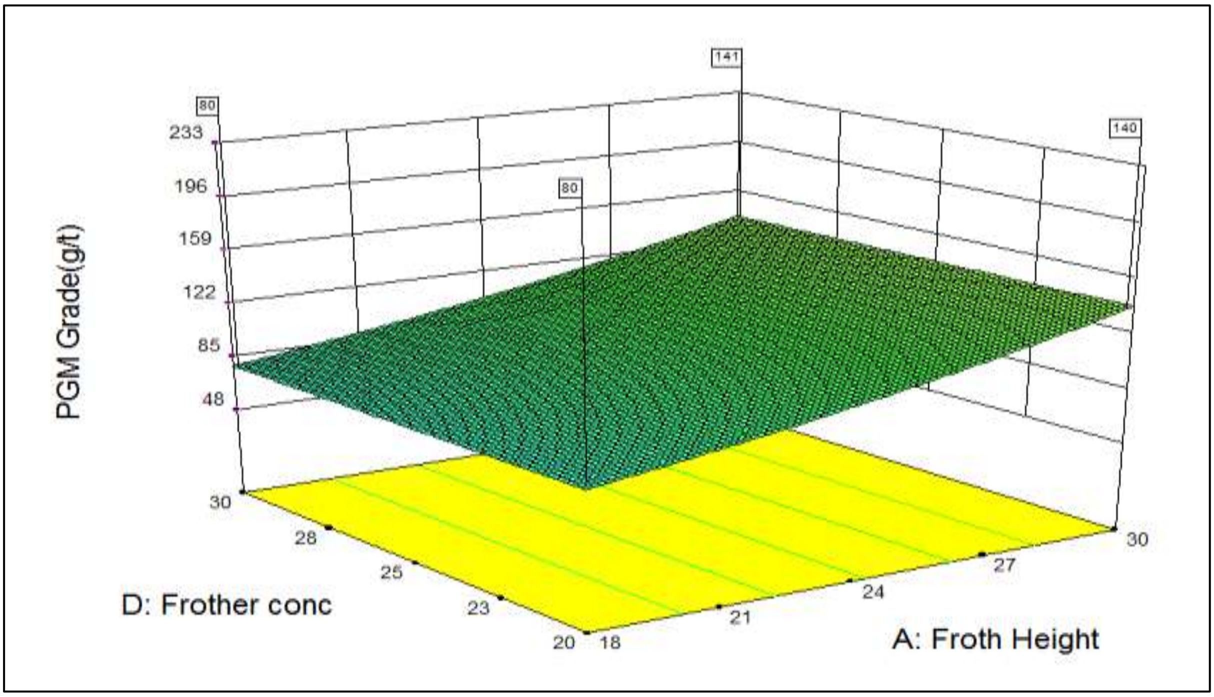


Figure 4.56 Effect of froth height and frother concentration on PGM grade keeping other factors at base level (1 cm/sec superficial air velocity & 200 g/t depressant dosage)

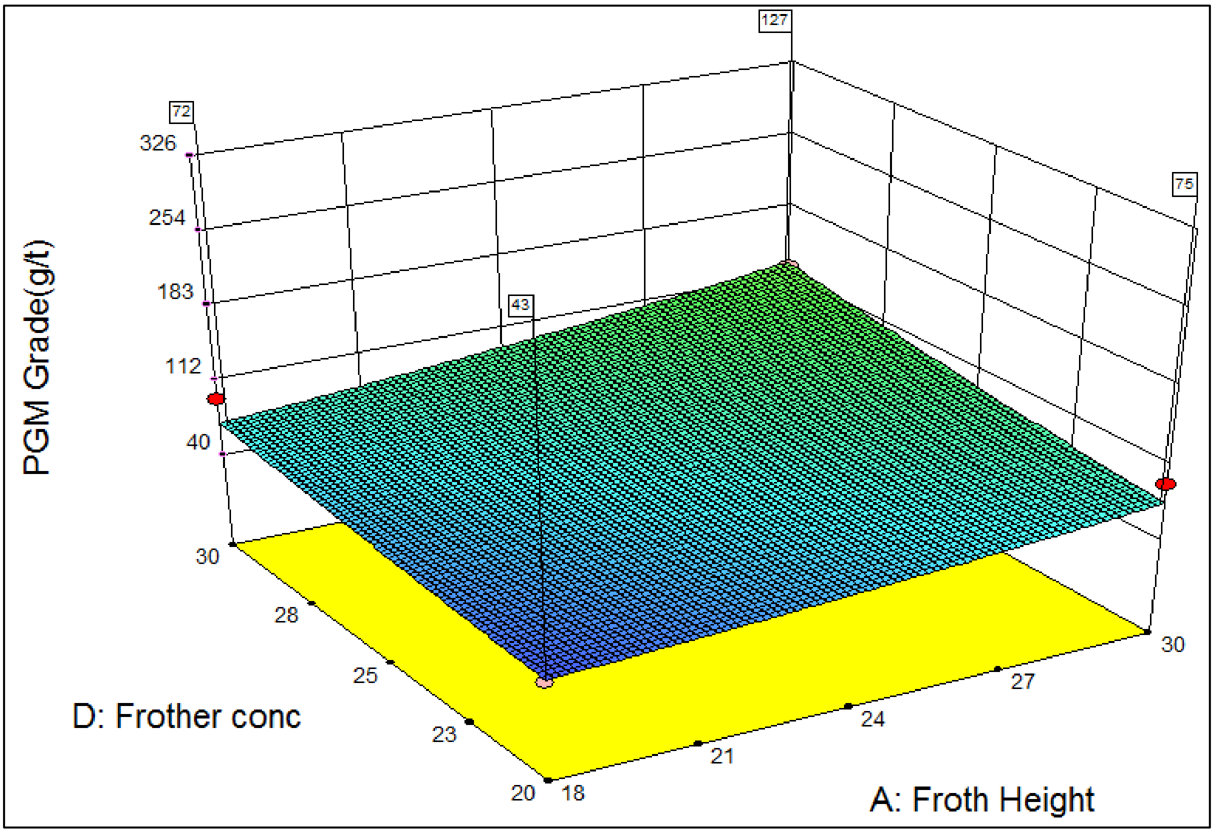


Figure 4.57 Effect of froth height and frother concentration on PGM grade keeping other factors at high level (1.5 cm/sec superficial air velocity & 300 g/t depressant dosage)

Table 4.5 Summarized results of froth height and frother concentration on PGM grade

Constant factors & levels	Variable Factors		Effects on Response
Superficial air velocity and Depressant dosage	**Froth height**	**Frother concentration**	**PGM grade**
@ Low level (0.5 cm/sec & 100 g/t)	Low to High	Low level	Increases
	Low to High	High Level	Increases
	Low Level	Low to high	Decreases
	High Level	Low to High	Decreases
@ Base level (1 cm/sec & 200 g/t)	Low to High	Low level	Increases
	Low to High	High Level	Increases
	Low Level	Low to high	No change
	High Level	Low to High	No change
@ High level (1.5 cm/sec & 300 g/t)	Low to High	Low level	Increases
	Low to High	High Level	Increases
	Low Level	Low to high	Increases
	High Level	Low to High	Increases

4.5.6.6 *Effect of Depressant Dosage and Frother Concentration on PGM Grade*

The effect of depressant dosage and frother concentration on PGM grade is shown in Figures 4.58, 4.59 and 4.60. While depressant dosage had no effect on PGM grade, increasing frother concentration either decreased, increased or had no effect on PGM grade, depending on the levels of the superficial air velocity and froth height.

At low levels of superficial air velocity and froth height, PGM grade decreased as frother concentration increased (Figure 4.58) At intermediate levels of air flow and froth height, PGM grade did not change as frother concentration increased (Figure 4.59). While at high levels of air flow and froth height, the PGM grade decreased as frother increased (Figure 4.60). The summarized results are given in Table 4.6

Table 4.6 Summarized results of depressant dosage and frother concentration on PGM grade

Constant factors & levels	**Variable Factors**		**Effects on Response**
Superficial air velocity and Froth height	**Depressant dosage**	**Frother concentration**	**PGM grade**
@ Low level (0.5 cm/sec & 18 cm)	Low to High	Low level	No change
	Low to High	High Level	No change
	Low Level	Low to high	Decreases
	High Level	Low to High	Decreases
@ Base level (1 cm/sec & 24 cm)	Low to High	Low level	No change
	Low to High	High Level	No change
	Low Level	Low to high	No change
	High Level	Low to High	No change
@ High level (1.5 cm/sec & 30 cm)	Low to High	Low level	No change
	Low to High	High Level	No change
	Low Level	Low to high	Increases
	High Level	Low to High	Increases

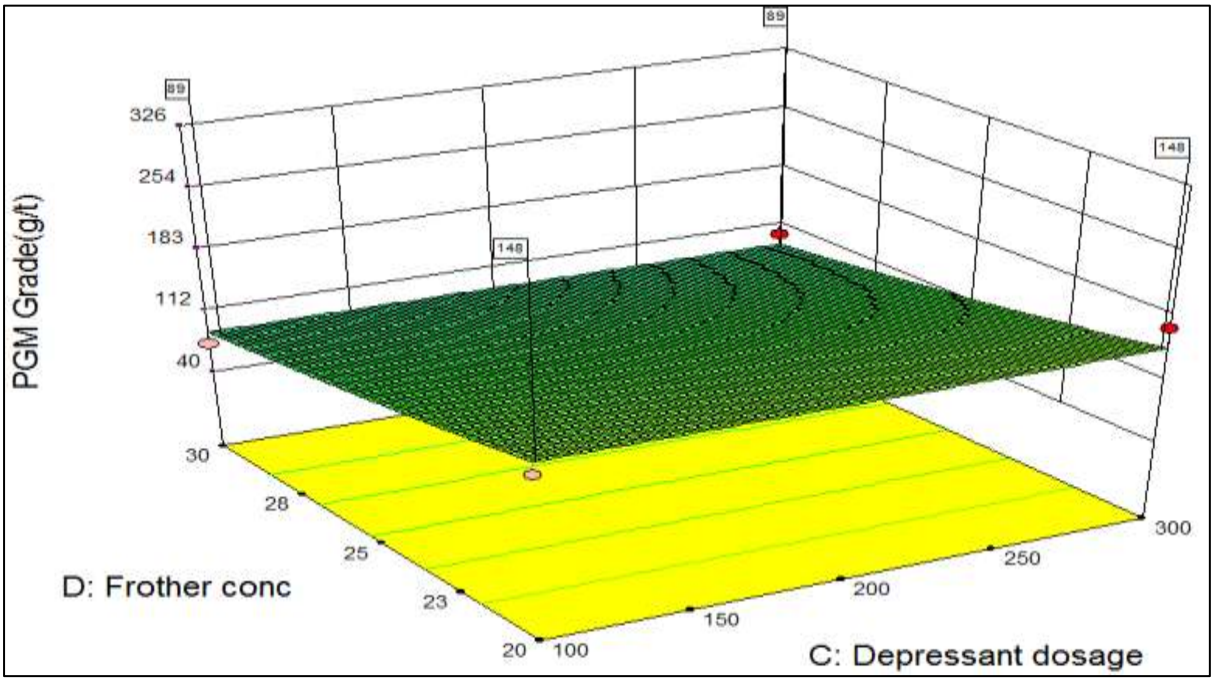


Figure 4.58 Effect of depressant dosage and frother concentration on PGM grade keeping other factors at low level (0.5 cm/sec superficial air velocity and 18 cm froth height)

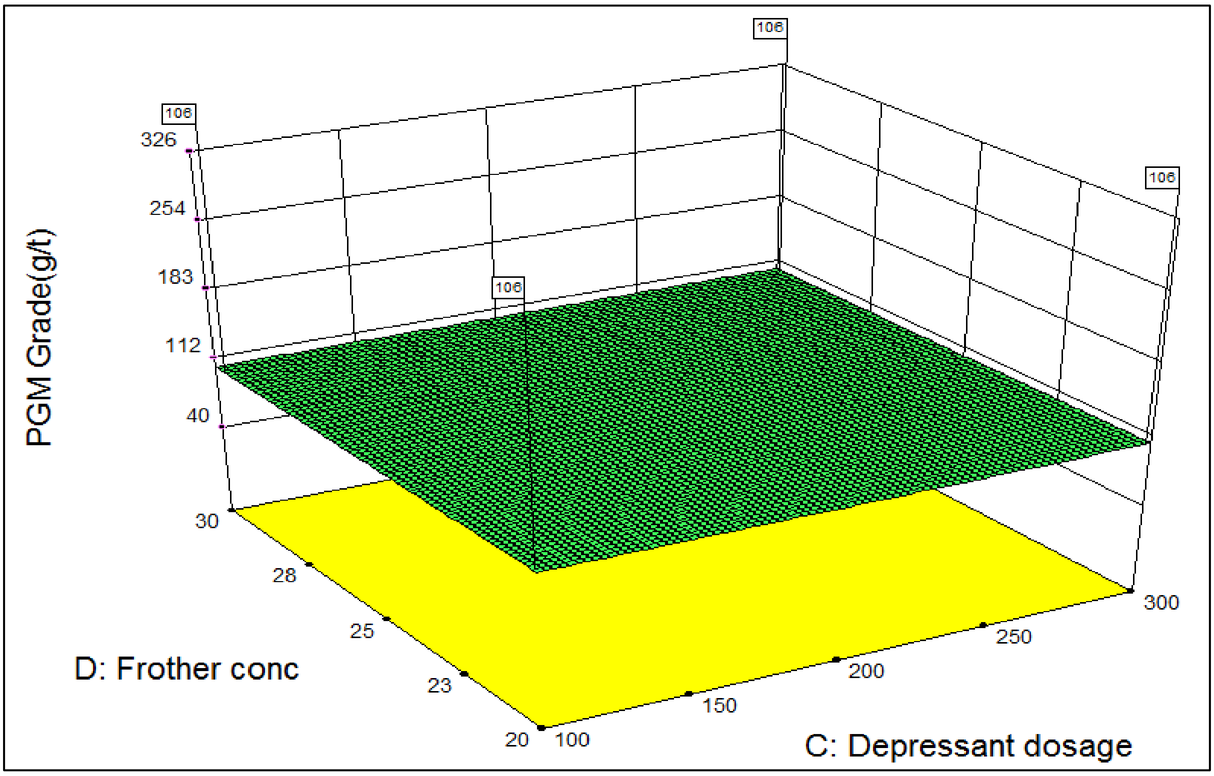


Figure 4.59 Effect of depressant dosage and frother concentration on PGM grade keeping other factors at base level (1 cm/sec superficial air velocity and 24 cm froth height)

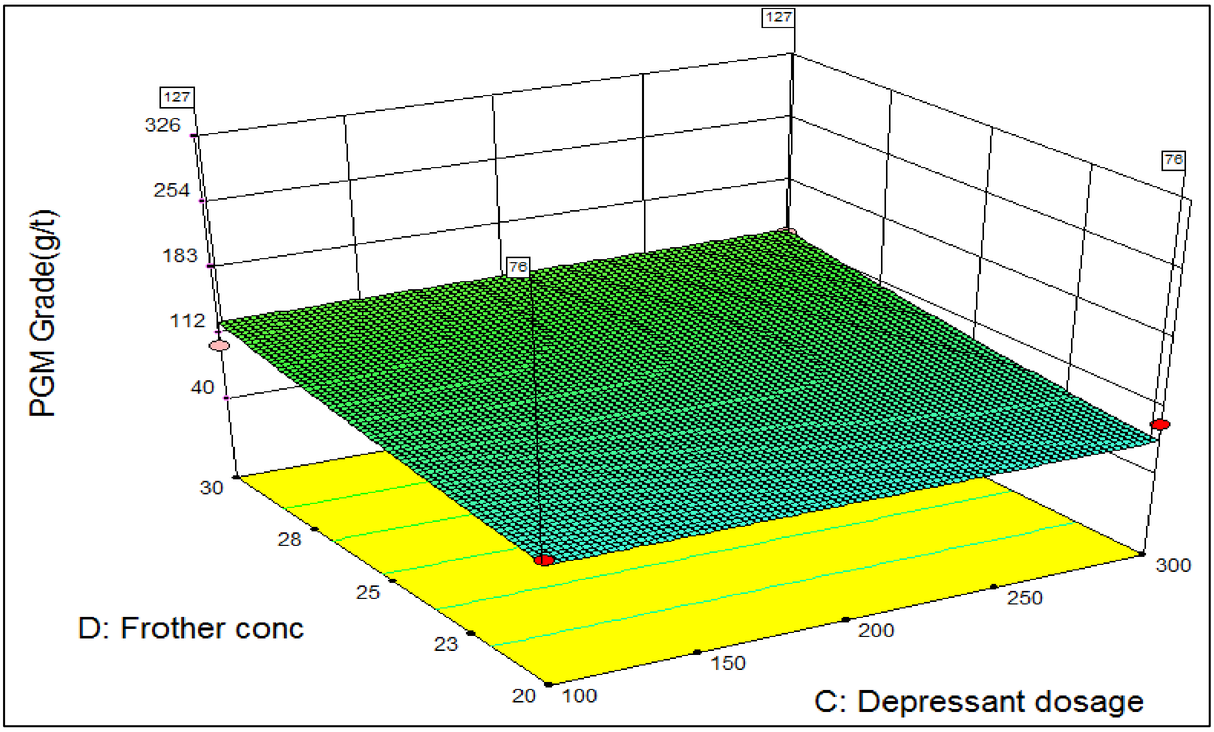


Figure 4.60 Effect of depressant dosage and frother concentration on PGM grade keeping other factors at high level (1.5 cm/sec superficial air velocity and 30 cm froth height)

5 Discussion

This chapter discusses the results and findings of the investigation. This study also explains the interactive effect of the process parameters and tries to fill the knowledge gap in the subject. In this section, the results are also discussed along with the main test work in order to validate proposed hypotheses.

5.1 Test at Base Level

It was observed that at low level of frother concentration (10ppm), the solids recoveries varied from 0.2g/min to 0.5g/min and water recoveries from 5 g /min to 10g/min which is very low as compared with high levels of frother concentration (30 ppm). This is because at 10 ppm frother dosage, the concentration is not sufficient to produce a stable froth. It should also be noted that a concentration of 10ppm is generally considered to be less than the CCC values for stable bubble formation in the pulp. The froths were observed to be unstable and brittle. Alike solid recovery and water recovery, observations were also made with chrome and PGM recoveries. The low recovery at 10 ppm of frother concentration may be attributed to the fact that the froth is unable to hold the mineralized bubble as the surface elasticity at the air-water interface is very low (Tan, 2005). Although the recoveries were low, the PGM grades increased significantly at low frother concentration since the amount of water reporting to the concentrate and, therefore, the amount of entrained gangue, decreased substantially. This resulted in a significant increase in grade (up to 1.7 kg/ton). The amount of chrome reporting to the concentrate was also very low (<0.1g/min). This is because the chromite is hydrophilic in nature and will report to the concentrate through mechanical entrainment only. As the mechanical entrainment is directly proportional to the water recovery, the low water recovery resulted in low chrome recovery in the concentrate. The particle size of the concentrate was found to be less than 50µm. Therefore, the coarse chromite reported to the tailings due to its mass.

Due to the extremely low mass pull, it was concluded that 10 ppm frother concentration was not sufficient for studying the interactive effect of factors by factorial design. Thus, the minimum frother concentration was changed from 10ppm to 20 ppm, and the experiments were repeated. The upper limit is kept at 30 ppm. The response of solids recovery, water recovery, chrome recovery, chrome grade, chrome recovery, PGM recovery and PGM grade with changing frother dosages are discussed in the following sub sections.

5.2 Response of Solid recovery

The response of solid recovery for the four factors was represented by the regression equation as given in Section 4.5.1

$$Solid\ Recovery\left(\frac{g}{min}\right) = 4.58 - 0.92FH + 1.75SAV + 0.5FC \quad (5.1)$$

Where FH = Froth Height, SAV =Superficial Air Velocity, FC= Frother Concentration respectively.

It was observed that the amount of solid recovery is most positively affected by the superficial air velocity and to a lesser extent by the frother concentration. The increasing superficial air velocity will increase the mechanical carryover of solid particles to the concentrates by ascending air bubbles. High superficial air velocities will increase the bubble surface area flux, S_b (which equals $6J_g/d_b$) (Finch et al., 2007), which increases the amount of solid recovery.

In case of frother concentration, the increasing amount of frother stabilizes the froth (Langevin, 2000) resulting in a greater attachment of solids to the air bubbles and hence resulting in recovery increases as shown in Figure 5.2. It is generally accepted that entrainment is the primary mechanism for the recovery of fully liberated gangue particles except in the case of naturally floatable gangue. With an increase in frother concentration, the hydrophilic entrained particles report to the froth suspended in the lamellae of water that surround the bubbles. This process is controlled by water recovery, and it is well known that the greater the water recovery the greater is the mechanical entrainment of hydrophilic gangue. However the change in solid recovery with change in frother concentration is not as prominent as change in solid recovery with superficial air velocity.

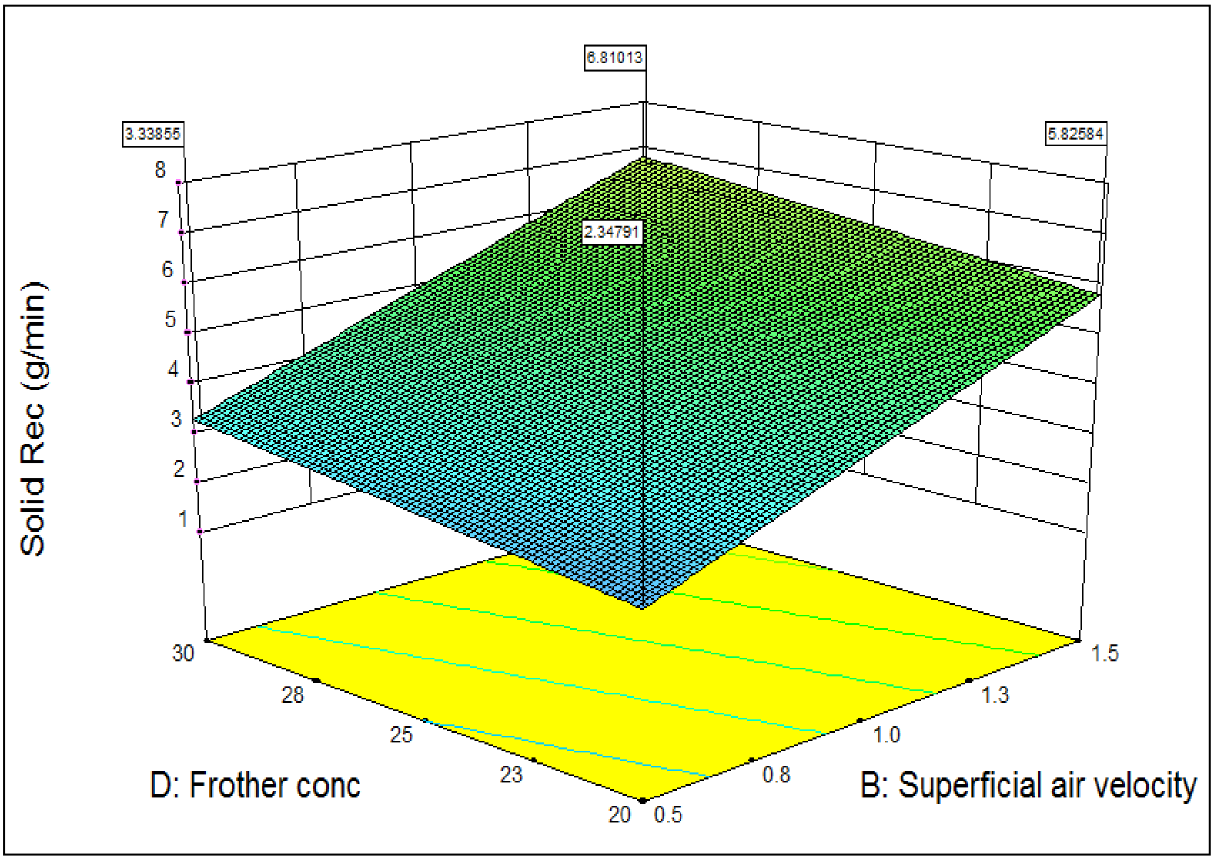


Figure 5.1 Effect of superficial air velocity and frother concentration on solid recovery

In the present study, the depressant dosage had very little or no effect on solids recovery. This can be explained from the characterization study of the feed sample (c.f Section 4.1). This is consistent with the observation that chromite, which constitutes more than 50 % of the gangue minerals in the ore, is not depressed by guar(Alvarez-Silva et al., 2012).

Guar gum however does depress the naturally floatable gangue minerals such as talc and serpentine. The amount of talc and serpentine in the ore is however relatively small (~2%) compared to other minerals and hence the depressant will have a minimal effect on the mass of solids recovered.

Equation 5.1 shows that increasing froth height (FH) reduced solids recovery. This is consistent with previous findings by other researchers (Finch et al. 1989; Neethling and Cilliers, 2002). Increasing the froth height will result in an increase in the drop back of particles from froth zone to pulp zone and hence the solids recovery will decrease. However the effect of increasing froth height was not as great as originally expected. The solids recovery at a froth height of 18cm was 7.73 (g/min) compared to a recovery of 5.85 (g/min) at a froth height of 30cm indicating a decrease of 25% in solids recovered when the froth height increased by 66%.

The interactive effects of the different parameters, for example the relationship between Froth height and superficial air velocity (FH)*(SAV), were less effective and insignificant compared to the individual effects at 95% confidence level. They were, therefore, discarded from the regression equation. Overall it was observed that the maximum recovery of solids can be achieved at high frother concentration (30ppm), high superficial air velocity and low froth heights. This is illustrated in Figure 5.1. This figure also illustrates that if the intention is to reduce solids recovery so as to reduce chromite recovery then a high froth height and a low superficial air velocity is required.

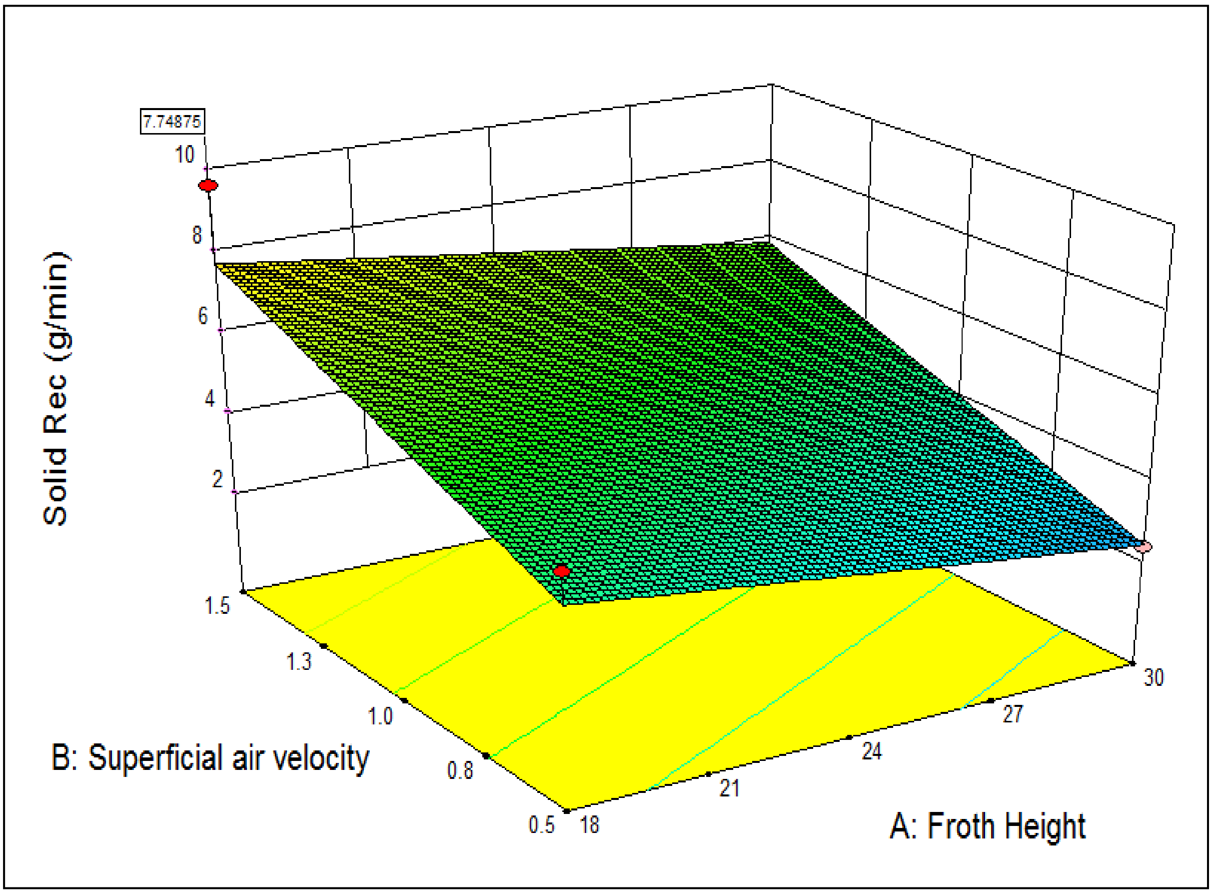


Figure 5.2 Response of solid recovery to superficial air velocity and froth height at high frother concentration (30ppm) and low depressant (100g/t)

5.3 Response of Water recovery

The response of water recovery for the four factors is represented by the regression equation as given in chapter 4 (cf.section 4.4.2).

$$Water\ Recovery\left(\frac{g}{min}\right) = 171.59 - 38.47FH + 57.75SAV + 43.03FC$$

$$-21.62SAV * DD * FC \qquad (5.2)$$

Where, FH=Froth Height, SAV=Superficial Air Velocity, DD= Depressant Dosage and FC= Frother Concentration

It appears from this equation (5.2) that the most significant factor affecting water recovery was the superficial air velocity followed by frother concentration and froth height. When the superficial air velocity is high, the froth is more mobile and increases the amount of water reporting to the concentrates (Hadler et al., 2012). It has been shown that as the frother concentration increases, the water carry-over that occurs by the bubble lamellae increases (Kitchener & Cooper, 1959). This is due to the Gibbs-Marangoni effect which proposes that if the lamellae are thinned, the concentration of frother molecules at the interface is disturbed from their equilibrium concentration. When excess frother molecules are present in the pulp, these will migrate to the interface of air-water and thus restore the equilibrium concentration resulting in more water being pulled in to increase the film thickness. A study by Wiese (2012) has also observed that increasing frother concentration resulted in an increase in water recovery. Equation 5.2 is consistent with that finding.

Increasing froth height had a negative influence on water recovery. This is because of the greater residence time in the froth phase as well as the lower froth mobility at high froth depths. This will result in the water draining back into the pulp. At low superficial air velocity and high froth height the residence time of air in the froth zone increases, resulting in lower water recovery (Savassi et al., 1998).

Equation 5.2 shows that depressant dosage did not have a significant individual effect on water recovery at the 95% confidence level. It did however have an overall interactive combined negative effect with superficial air velocity and frother concentration on water recovery (cf. section 4.4.2.2 and 4.4.2.6). At high frother concentration, high superficial air velocity and low froth height the water recovery increased. However an interactive effect was observed in that the presence of depressant dampened the effect of the frother concentration and the superficial air velocity on water recovery. Depressants are used to depress the naturally floatable gangues. At low depressant dosage these particles are less depressed and thus will report to the concentrates, resulting in greater solids recovery. Conversely, high depressant dosages will result in less solid particles reporting to the froth and this will have a destabilizing effect on the froth phase thus tending to reduce the water recovery. This is a widely observed effect and it is interesting to note that notwithstanding this effect of depressants on water recovery it is less significant than the individual effects of froth height, air velocity and frother concentration.

5.4 Response of Chrome Recovery

The effect of factors for chrome recovery was studied and the regression equation was developed (cf. section 4. 5) to represent chrome recovery.

$$Chrome\ Rec\left(\frac{g}{min}\right) = 0.62 - 0.13 * FH + 0.30SAV + 0.077FC \qquad (5.3)$$

It should be noted that this equation indicates the rate of chrome recovery. This is because of the use of a continuous open circuit system (column flotation cell) and provides the results of a steady state operation. From the regression equation 5.3 it can be seen that the chrome recovery rate is strongly affected by superficial air velocity, froth height and less by the frother concentration. The effect of depressant dosage on chrome recovery is less than 2% and is not shown in the regression equation 5.3. The depressant used to depress the silicate gangue minerals did not have any effect on chromite. This is similar to observations made by Valenta (2007) and Alvarez-Silva et al. (2012) in a similar system. The effect of superficial air velocity had the most significant positive effect on chrome recovery. When the superficial air velocity is increased at constant froth depth, there is a decrease in the residence time of the air in the froth zone leading to more chromite entrainment in the concentrate. This is because the increase in superficial air velocity resulted in more carryover of solid and water that lead to the mechanical entrainment of chromite. Similarly increasing froth height increases residence time of air in the froth zone, resulting in drop back of particles and less chromite report to the concentrate. If the superficial air velocity and froth depth are increased together, then there is an increase in chrome recovery. This shows that the superficial air velocity is a more powerful driver of water recovery (and hence chrome recovery) than the froth height within the selected range. The residence time of air, which is defined as the ratio of froth height to superficial air velocity in the froth zone (FH/SAV), has a proportional effect on entrainment (Savassi et al, 1998). At a particular froth height, the froth residence time decreases with the increase in the superficial air velocity. The chromite recovery vs residence time of air in the froth is shown in Figure 5.2. This figure shows that at 20 ppm frother and a depressant dosage of 100g/t or 300g/t, the longer the froth residence time, the lower the rate of recovery of chrome. At 30ppm frother concentration and 300 g/t of depressant the chrome recovery rate plateaus at residence times longer than 20s. At the higher depressant dosage there will be little or no floatable gangue in the concentrate and the higher recovery of chrome may be due to a lower crowding effect of gangue minerals other than chromite in the froth phase. The higher frother concentration may increase the froth stability. The lower frother concentration does not adequately compensate for the reduced number of froth stabilizing particles in the froth and so the chromite recoveries are reduced.

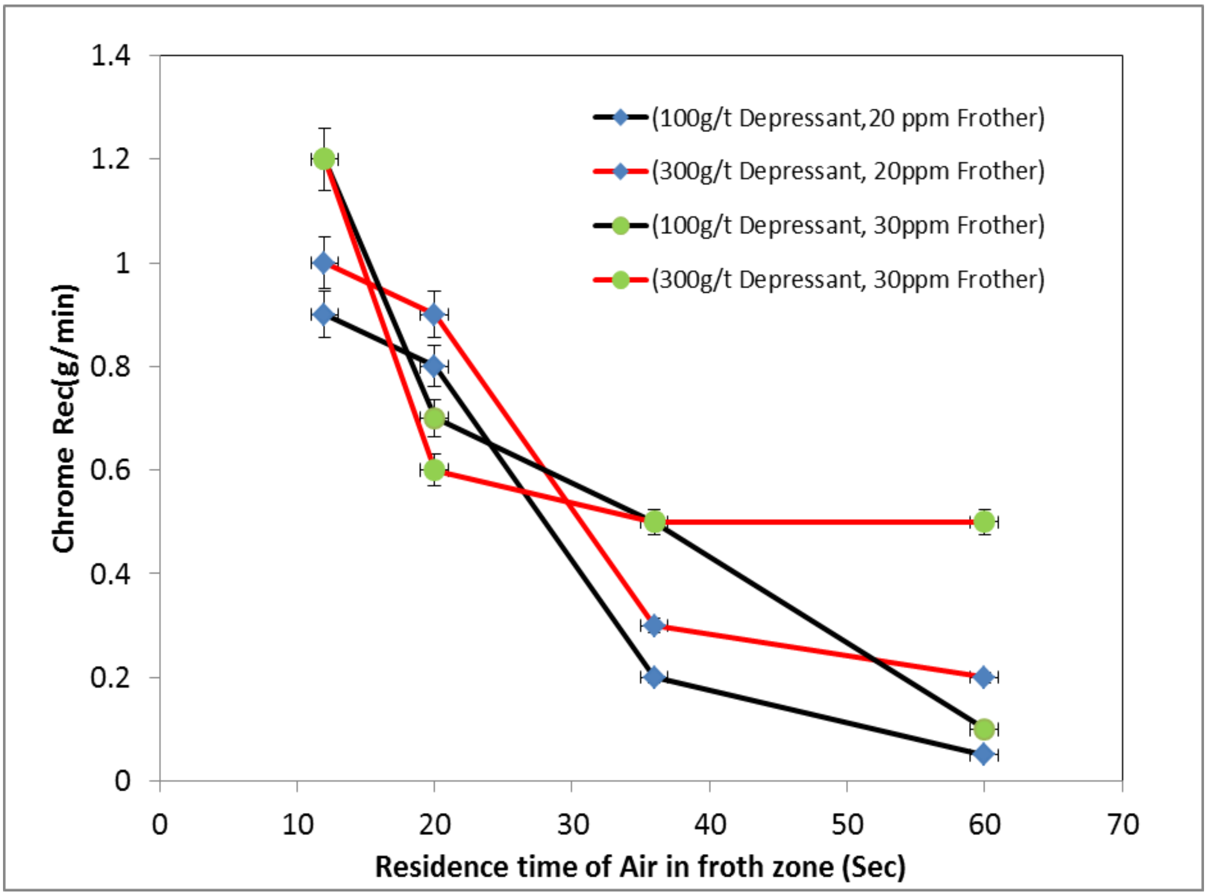


Figure 5.3 Effect of froth residence time of air on chrome recovery

5.5 Response of Chrome Grade

The effect of the process parameters on chrome grade is shown in the regression equation 5.4 (cf. section 4.6).

$$\begin{aligned} \mathit{Chrome\ Grade}(\%) \\ &= 11.68 - 0.85FH + 1.30SAV + 1.96DD + 0.76FC + 0.45FH * DD \\ &- 1.19SAV * DD - 0.52SAV * FC - 067FH * SAV * DD \qquad (5.4) \end{aligned}$$

This equation shows that the chromite grade is dependent on all four process parameters, with the depressant dosage having the major individual effect. This is not surprising since as the depressant dosage increases less of the naturally floatable gangue will report to the concentrate meaning that the concentrate will be a relatively higher concentration of chromite. Moreover, as already alluded, depressants have no effect on the recovery of hydrophilic chromite. Superficial air velocity and froth height have a similar effect on the chrome grade as they did on chrome recovery. The increase in these parameters resulted in an increase in the grades. The increase caused by an increase in air velocity is understandable since there be a greater upward flux of solids and water arising from such changes. However, an increase in depressant dosage selectively depresses the naturally floatable gangue and thus increases the chrome grade in the concentrate.

Figure 5.4 shows that higher superficial air velocities and depressant dosages increased chrome grades. This is because the individual influence of depressant dosage and superficial air velocity are greater than the combined effect.

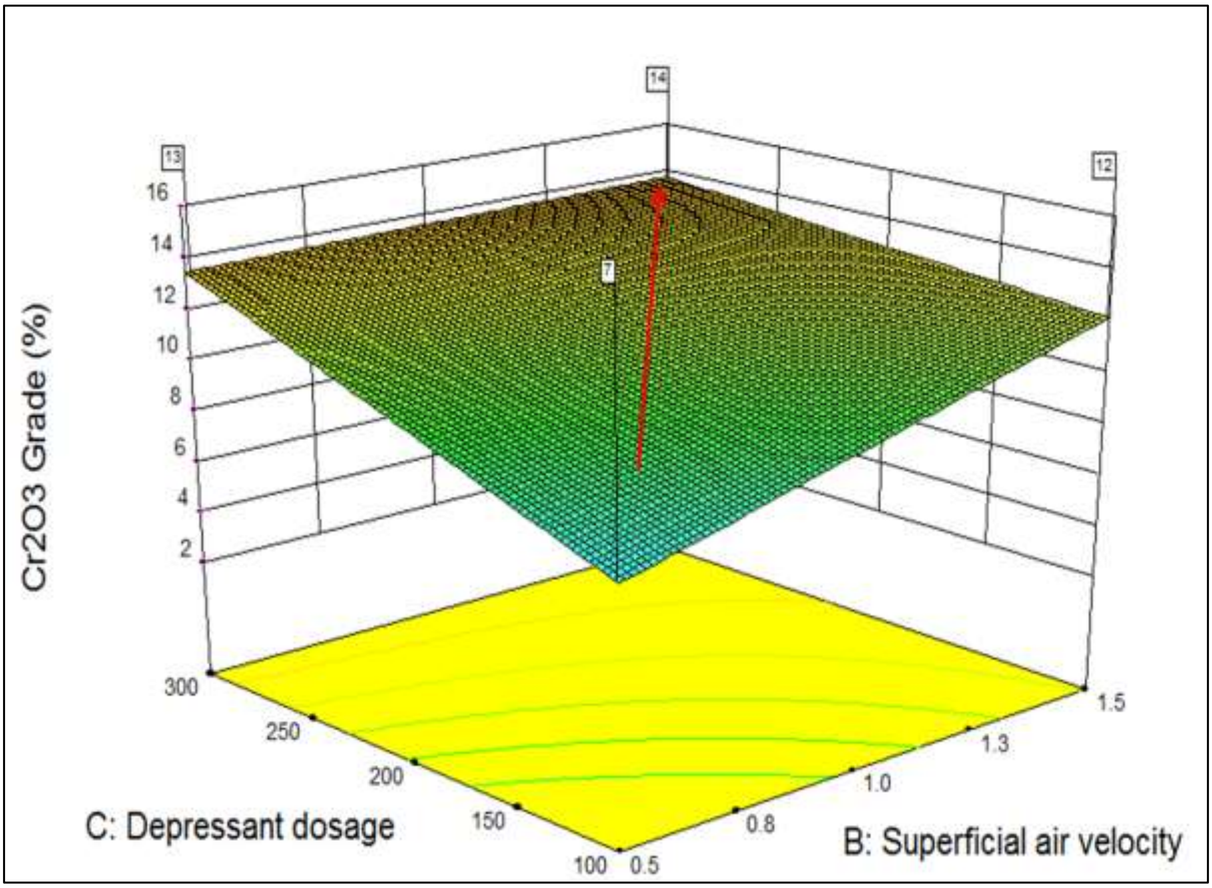


Figure 5.4 Effect of superficial air velocity and depressant dosage on chrome grade

Figure 5.5 shows the influence of depressant dosage on chrome grade for different frother concentrations and residence times of the air in the froth zone. At low residence times of air (high superficial air velocity and low froth depth) the chrome grades are fairly similar for all the depressant dosages (300g/t). There is a reduction of gangue particles in the froth phase. This will result in an increase in the chrome grade. However this should also result in a less stable froth. The higher frother concentration of 30g/t resulted in an increase in the chrome grade indicating that this contributed to stabilizing the froth enabling the entrained chrome to be recovered. The lower depressant dosages resulted in a low chrome grade because of the continued reporting of gangue to the concentrate. Naturally increasing the frother concentration did not affect this since it would only have served to incrase froth stability and this would contribute to chrome recovery and hence an increase in chrome grade.

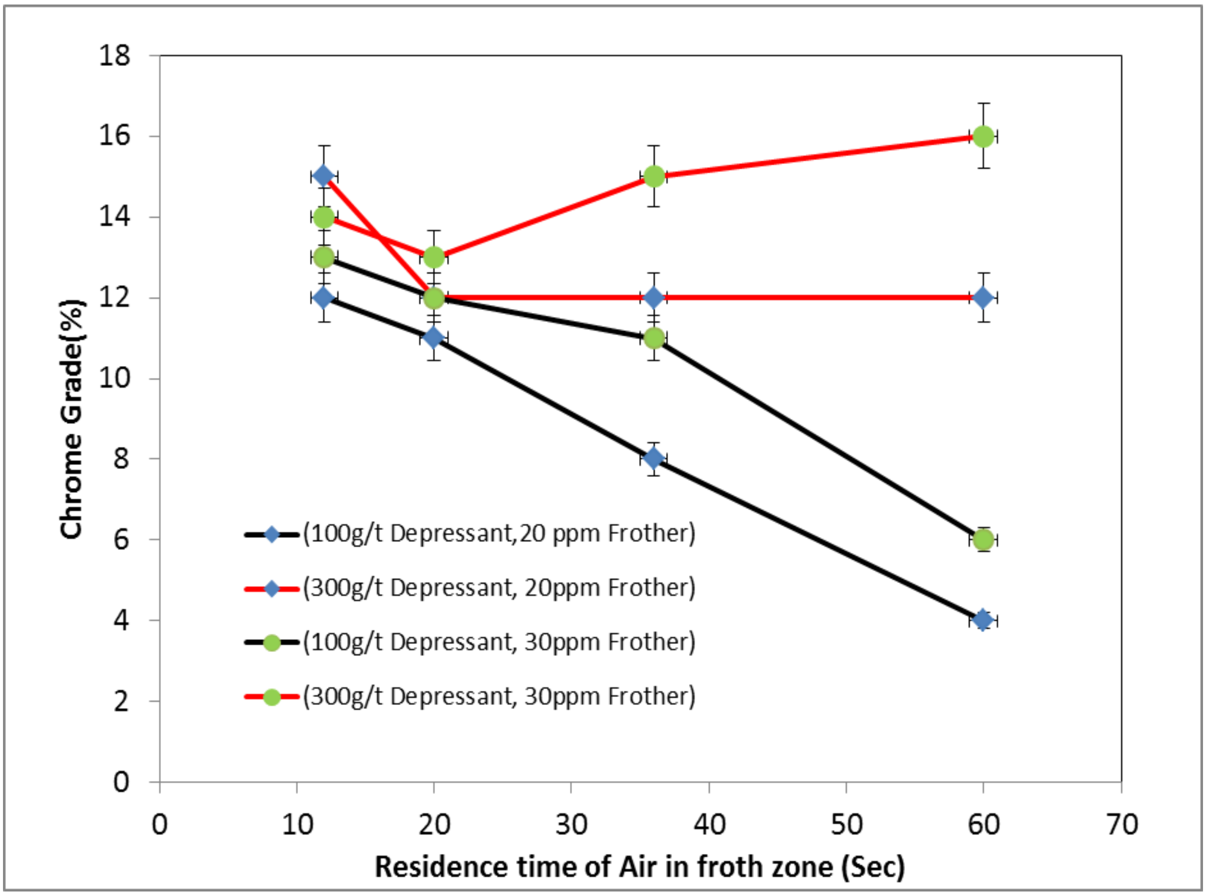


Figure 5.5 Effect of froth residence time of air on chrome grade

5.6 Response of PGM Recovery

The regression equation 5.5 shows that the effect of the four variable process parameters on the recovery of PGMs was relatively minor. Across the whole range of conditions the PGM recovery varied between 66% and 72 %.

$$PGM\ Rec\ (\%) = 69.21 - 0.86FH + 1.16SAV - 0.55 * SAV * DD - 0.31 * FH * DD * FC \qquad (5.5)$$

From the regression equation, it can be observed that the recovery of PGMs increased with an increase in superficial air velocity and decreased as the froth height increased. At higher froth heights the drop back of particles would increase resulting in less mass pull to the concentrates. Moreover the PGM ore particles are relatively dense and this would further increase the drop back phenomenon. A study carried out by Alvarez-Silva et al (2012) found that the recovery of PGMs was not strongly dependent upon froth height. However in this study it was shown that the froth height had a relatively negative effect on the recovery of PGMs.

At 66% PGM recovery (high froth height, low superficial air velocity, low frother concentration and high depressant dosage) the PGM grade found to be 260 g/t and there was a considerable loss of PGMS in the tailings while at 72% recovery the grade was 150g/ton with 30% of PGMs in the tailings. Equation 5.5 shows that there were interactive effects between depressant dosage and superficial air velocity as well as between froth height, depressant dosage and frother concentration. In the interactive effects it can be observed that the combined effect of depressant dosage and superficial air velocity had a negative effect on PGM recovery. This may indicate that there is a loss of PGMs which are non-liberated (i.e. still locked in a gangue matrix). Since increasing air velocity on its own increased recovery this result indicates that the effect of depressant cannot be compensated for by a higher air velocity. The combination of depressant dosage, froth height and frother concentration had a negative influence on PGM recovery. High depressant dosages will reduce recovery of non-liberated PGMs and this will be compounded by the higher froth height. Increased frother concentration may stabilize the froth possibly allowing for as longer froth residence time during which PGMNs may drop back into the pulp. This is because the froth height and depressant dosage dominated the frother concentration.

5.7 Response of PGM Grade

The effect of process parameters on the response of PGM grade is shown in the regression equation 5.6.

$$Ln\left(PGM\ grade\left(\frac{g}{t}\right)\right) = 4.66 + 0.29FH - 0.36SAV + 0.26SAV * FC \qquad (5.6)$$

From the regression equation it can be seen that not surprisingly increasing froth height results in an increase in grade. Considering equation 5.5 which showed that increasing froth height reduced recoveries this shows that the greater effect of froth height was to reduce gangue recovery resulting in an increase in grade. The lost gangue is probably the relatively more dense chromite. On the other hand increasing air velocity increased recovery and reduced grade. This appears to indicate that the greater effect of increasing air rate is to increase gangue recovery more than PGM recovery. Increasing the superficial air velocity within the current range will also result in larger bubble surface area flux (Finch et al., 2007). This will result in an increase in recovery of gangue minerals through entrainment. The increased entrainment results in a decrease in grade of PGMs in the concentrate. With an increase in froth height the drop back of particles from the froth zone to the pulp zone increases. The resulting increase in grade may indicate that it is the gangue particles which are mostly lost in this manner and these may be the relatively dense chromite particles. Thus the grade of the concentrate is increased.

The depressant dosage had very little effect on PGM grade at the 95 % confidence level so the effect of depressant dosage was not included in the model used for PGM grade. Since it has already been shown that the major gangue mineral is chromite and that depressants do not affect chromite recovery since it is entrained this result is to be expected. The frother concentration also had no individual effect but there was a combined positive effect of frother concentration with superficial air velocity. At low air flow rate the negative impact of increasing frother concentration is greater than at high air flow rates. This suggests that the effect of increased air flow overrides the effect of increased frother within the ranges chosen. At the higher froth height (30cm) and higher superficial air velocity (1.5 cm/sec) the PGM grades increased with an increase in frother concentration because of the interactive effects. But overall, the PGM grade decreased as frother concentration increased. These observations are shown graphically in Fig 5.6.

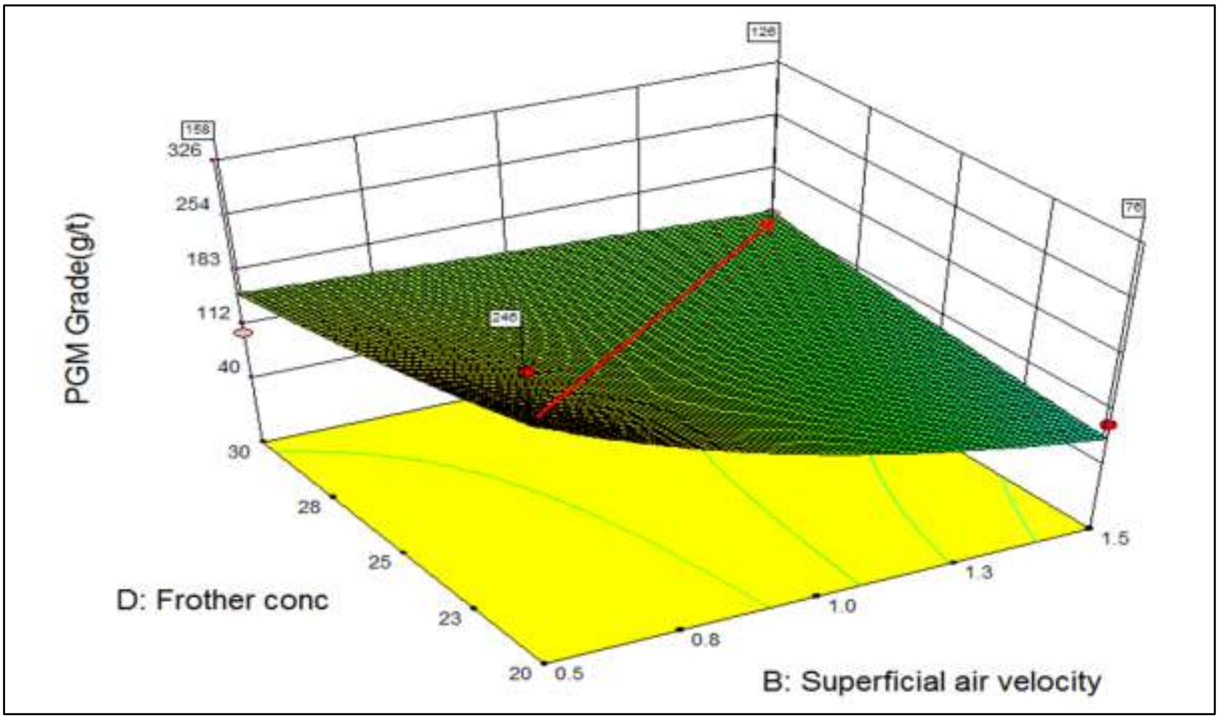


Figure 5.6 Effect of superficial air velocity and frother concentration on PGM grade

5.8 Effect of Major Factors and their Contributions on all the Responses

The effect of the major factors and their contributions for different responses studied are shown in Figure 5.7. For the purposes of the following part of the discussion it will be assumed that any effect which makes a contribution >20% will be considered significant. This is an entirely arbitrary judgement but will be used simply to focus the discussion. Using this criterion the degree of contribution of the process parameters on the responses follows this order:

Superficial air velocity > Froth height > Frother concentration > Depressant dosage

It can be seen that the superficial air velocity is the major contributor in the case of all the responses except for chrome grade. Superficial air velocity is known to affect the following

(i) Bubble surface area flux (S_b): The bubble surface area flux (S_b) is defined as the ratio of superficial air velocity to bubble size (bubble surface area flux(S_b= $6J_g/d_b$) (Finch & Dobby, 1990). It should however be noted that as J_g increases the bubble size will increase. However in the present case the frother concentration is 20ppm and it is assumed that this value is approximately equal to the critical coalescence concentration (ccc) at which point bubble size becomes almost constant. Thus Sb will probably increase as J_g increases.

(ii) Collection zone rate constant (k_C): Since kc equals 1.5 Ek jg d_b^{-1} if d_b is roughly constant and it is assumed that collection efficiency Ek is also constant at constant chemistry and hydrodynamic conditions then it can be assumed that kc will increase as J_g increases.

(iii) Overall Rate Constant (K_c): The overall rate constant has been shown to best equate to PSbRf where P is a property of the ore type, and Rf is the fraction of those valuable minerals that report to the pulp-froth interface which eventually reach the launder. Hence Kc will increase as J_g increases.

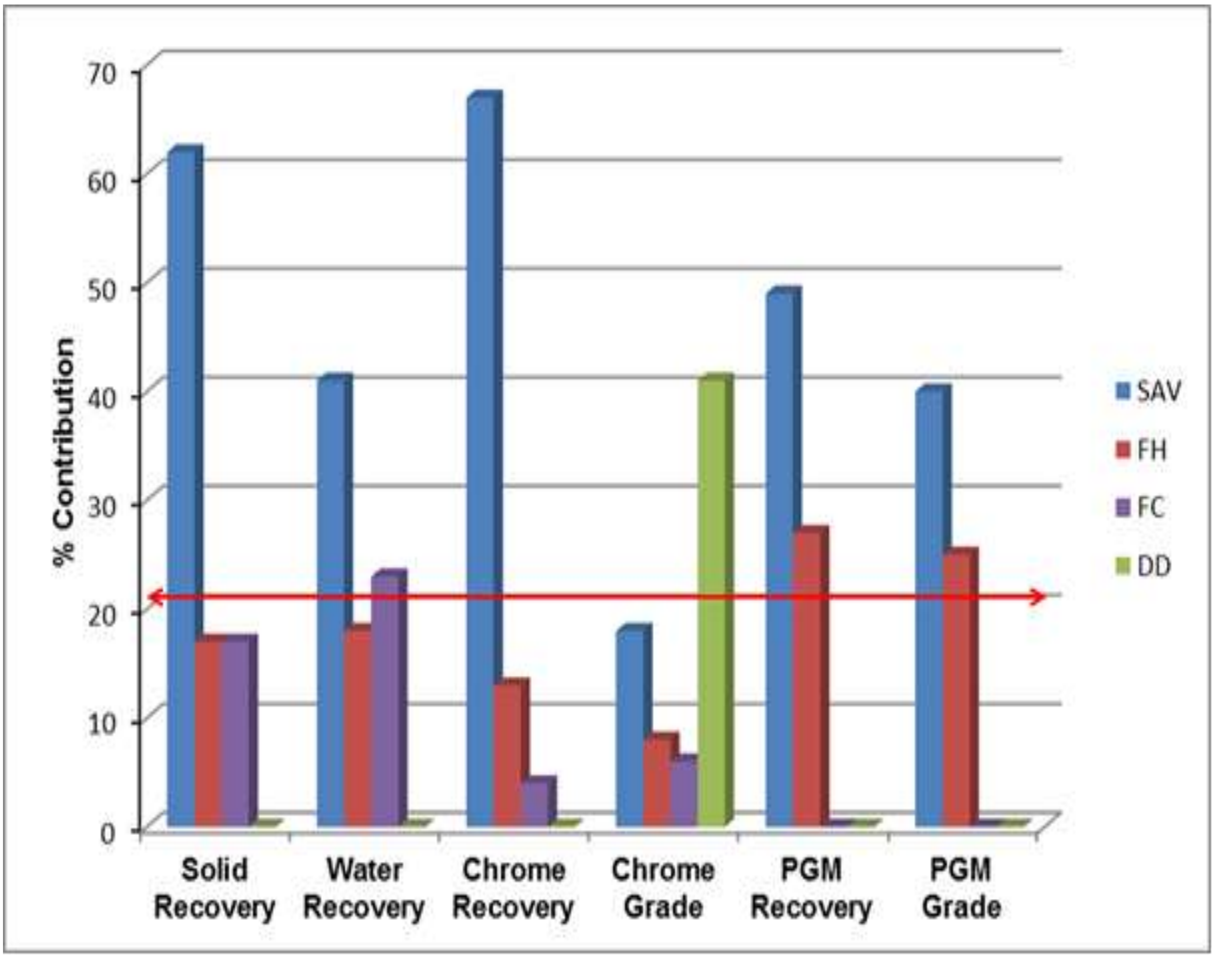


Figure 5.7 Effect of factors and their % contribution on different responses

(SAV= Superficial air velocity , FH = Froth height, FC = Frother concentration, DD= Depressant dosage)

According to Finch and Dobby (1990), the effect of superficial air velocity also affects the gas holdup (ε_g). The gas holdup increases with an increase in superficial air velocity to a maximum. At greater jg values the system starts bubbling and the recovery decreases (Figure 5.9) (Finch et al., 2007). Dobby (1984) also found that a maximum recovery was observed at a superficial air velocity of ~1.5 cm/sec (Figure 5.8). In the present investigation, the superficial air velocity varied from 0.5cm/ sec to 1.5 cm/sec and so the latter value was in the region of the optimum value proposed by Dobby.

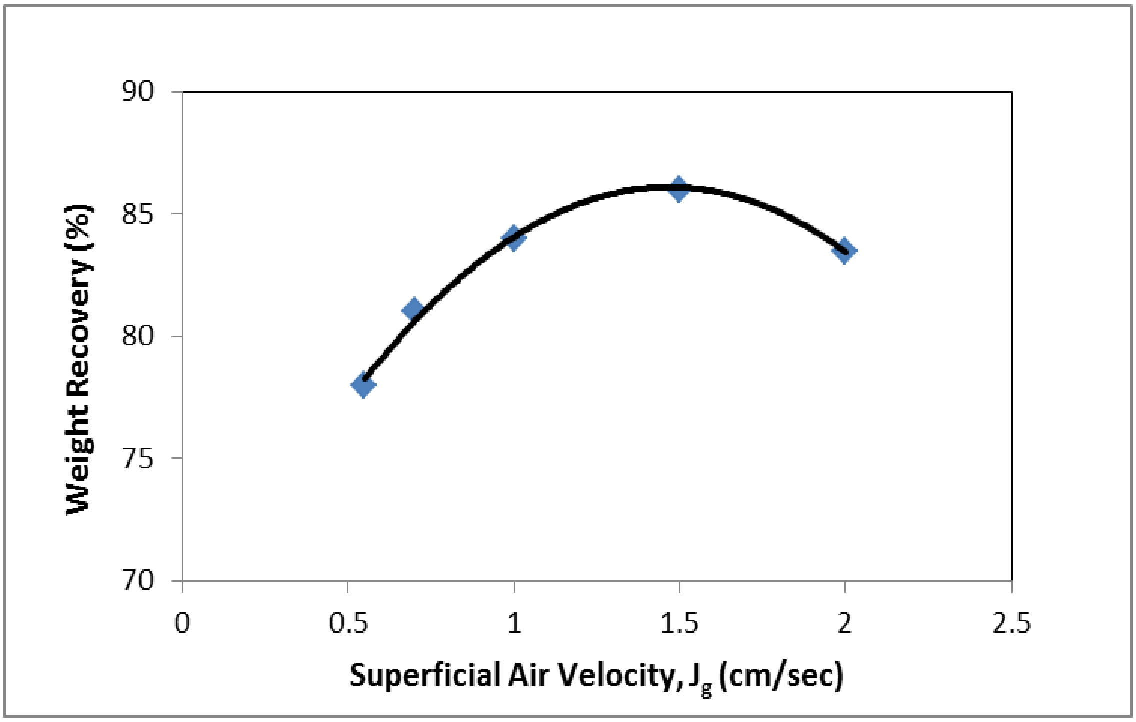


Figure 5.8 Effect of superficial air velocity on weight recovery (Dobby, 1984)

From the Figure 5.8, it shows that the transition point is 1.5 cm/sec So before transition point the recovery increases with increase in gas velocity. After the transition point the recovery decreases.

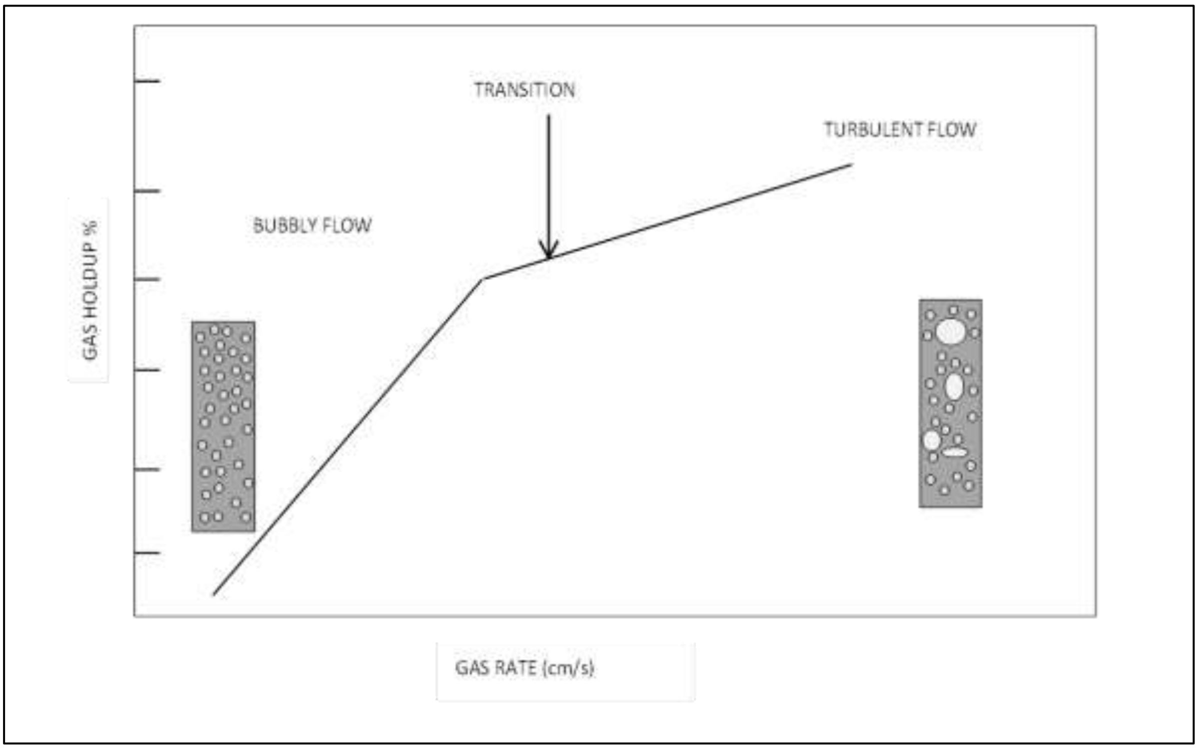


Figure 5.9 Effect of gas rate on gas hold up (Finch et al.,2007)

As referred to above Finch and Dobby (1990) proposed that there is a relationship between the superficial air velocity, collection efficiency and bubble size for collection rate constant (k_c), and this is shown in equation 5.7.

$$k_c = 1.5 J_g E_k d_b^{-1} \qquad 5.7$$

where, J_g = Superficial air velocity

E_k= Collection efficiency and

d_b = Bubble size

Equation 5.7 implies that an increase in superficial air velocity increases the collection zone rate constant and thus increases all the recoveries. The rate constant is inversely proportional to the bubble size , i.e. smaller the bubble size, higher will be the rate and hence the recovery. In the present study the bubble size is probably not affected by the frother concentration as the critical coalescence concentration for the Dow 200 is around 20ppm (0.18 mmole/dm^3). Cho & Laskowski (2002) studied the effect of frother concentration on bubble size and indicated that at concentrations greater than critical coalescence concentration (CCC), the bubbles cease to coalesce and the size of bubbles becomes constant and is hardly affected by increases in frother concentration (Figure 5.10). Thus, the increase in all recoveries as the superficial air velocity increases will be a result of the increased rate constant. It is important that although the PGMs recoveries increased with the an increase in superficial air velocity; this was accompanied by an increase in recovery of unwanted gangue minerals like chromite thus causing the PGM grades to decrease.

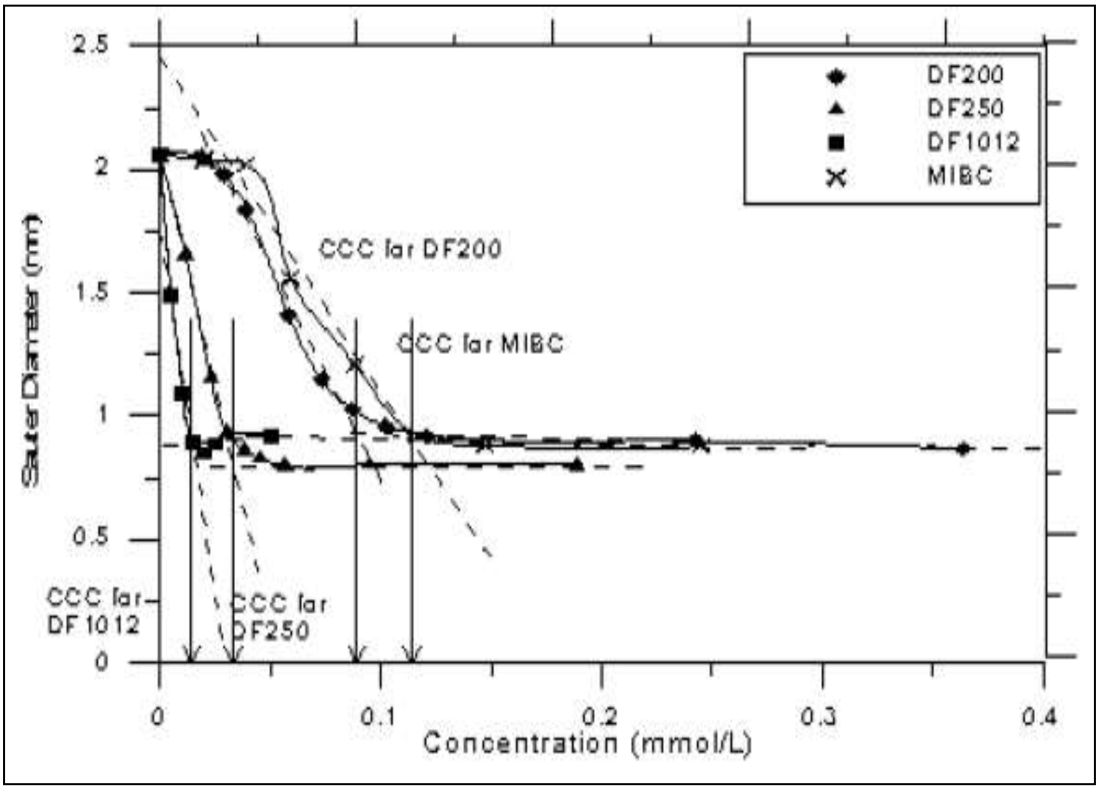


Figure 5.10 Effect of frother concentration on bubble diameter (Cho & Laskowski, 2002)

As already alluded to the overall rate constant (K_c), is a function of bubble surface area flux (S_b) and froth recovery (R_f) (equation 5.8) (Gorain et al.,1998). P is a constant indicative of the ore type.

$$K_c = PS_bR_f \qquad (5.8)$$

The froth recovery factor, R_f, depends upon the froth height and froth stability (Runge et al., 2010). The superficial air velocity and froth height are contending to each other in this domain. Although an increase in the froth height will result in a decrease in the froth recovery (R_f) and hence a decrease in Kc, the results of this investigation have shown that the effect of an increase in the superficial air velocity (J_g) is greater than the effect of froth height as indicated by the coefficients of SAV (superficial air velocity) and FH (froth height) in Eqs.5.1, 5.2, 5.3 and 5.5. However in some cases such as a high froth height (30cm) and low superficial air velocity (0.5 cm/sec), the recovery was lower than that observed at a low froth depth(18cm) and high superficial air velocity (1.5cm/sec).

The effect of froth height is the second greatest contributor found in this study. Yianatos et al., (1988) have shown that the grade profile of different minerals varies with different froth height. Froth height has an effect for PGM recovery and PGM grade. In case of other responses, the effect is not so profound. The PGM minerals are heavier than the chromite minerals (density of Cr = 7.14g/cm3 and of Pt = 21.45g/cm3). Hence when the froth height is increased, the chances of drop back of PGM minerals from froth to pulp is probably greater than in the case of chromite and decreases the recovery and increases the grade of PGMs. However it should be noted that the PGM minerals are recovered by true flotation and hence are attached to bubbles whereas the chromite is recovered by entrainment and hence are not attached to bubbles.

The frother concentration had no significant effect on other responses except water recovery. Frother concentration mainly affects bubble size and it has already been noted that at the concentrations used in this study the bubble size was probably fairly constant. The frother concentration had a positive effect on water recovery. This is probably due to the effect which the frother concentration had on the stability of the froth phase.

It has been shown (Wiese, 2009; Wiese et al., 2010), that depressants reduce the recovery of the naturally floatable gangue (NFG) minerals thus reducing the mass of solids in the froth phase. This would reduce the stability of the froth and thu reduce the recovery of water as well as the solids.. In the present investigation, depressant dosage was found to only affect the chromite grade (Eqn. 5.4) due to the reduction in the amount of gangue minerals reporting to the concentrate. The depressant has no effect on chromite which is recovered due to entrainment. The chromite content in the UG2 ore significantly high (52%) compared to the amount of NFG minerals. The depressant will reduce the recovery of all the NFGs thus resulting in an increase in the grade of the chromite (Eqn. 5.4). The depressant dosage did not have any effect on chrome recovery (Eqn. 5.3).

6 Conclusions and Recommendations

6.1 Conclusions

This thesis investigated the individual as well as interactive effect of process parameters for different responses. It was observed that the individual effect of the factor superficial air velocity was found more influential than other three process factors as well as their interactions for different responses. The frother concentration played a major role on the different responses when a wide range was selected (10 to 30ppm). At 10 ppm frother concentration, the recovery and mass pull was very low due to the low froth stability. At this range (10 to 30 ppm) the effect of frother concentration dominated the other factors. The depressant dosage was not significant for all the responses except chrome grade. Depressant dosage had no effect on hydrophilic chromite entrainment. The froth height had little effect on chromite entrainment but it had a reasonable effect on PGM grade and recovery. The conclusions drawn for all the effects at different responses are summarized in subsequent subsections.

6.1.1 Effect of Froth Height

The froth height had a quite substantial negative effect on PGM recovery. The regression equation showed a 27% negative contribution to PGM recovery. However, on the other hand, the positive effect on grade was similarly significant (25%). In a plant setting, PGM losses at deep froths would be minimised due to the losses in the first cells being recovered further down the bank. The positive effect on PGM grade is crucial in saving transport and smelting costs. Froth height, in addition to improving the PGM grade by draining silicate gangue, also reduced the chrome recovery. This is another significant savings in smelting penalties.

6.1.2 Effect of Superficial Air Velocity

The superficial air velocity was a primary contributor for all of the responses of grade and recovery. This is, perhaps, not surprising in view of the fact that air flow rate has a direct effect on the recovery in the pulp phase and the stability of the froth. The air flow rate had a large effect (41%) on water recovery. This would obviously have a large impact on entrained gangue, which is reflected in increased solids recovery (62% contribution to the regression equation), decreased PGM grades (40%) and large increases in chrome recovery (67%). These negative effects are mitigated to some extent by an increase in PGM recovery with increasing air flow rate. It is, however, known that a further increase in air flow rates past an optimum level will bring a levelling off, or even decrease in PGM recovery (Hadler et al, 2010). The very large effect of air flow rate may be a reflection of the range chosen, which was relatively large (0.5 to 1.5 cm/s). However, these are all plausible superficial gas velocities that have been observed on process plants and this study emphasises the need to have careful control over the air flow rate.

6.1.3 Effect of Depressant Dosage

The depressant dosage had very little effect for all the responses except the grade of chromite. The grade of chromite increased with increase in depressant dosage. This is due to the depression of naturally floatable silicate gangue minerals. This study showed that, for this system, the use of depressant was detrimental to optimising flotation conditions. It had little positive effect on PGM grade, but increased chromite grade in the concentrate which would result in the concentrate having to be diluted before going to smelter.

6.1.4 Effect of Frother Concentration

The effect of the chosen range of the parameter was demonstrated with frother concentration. Initially, the frother concentration ranged from low at 10ppm to high at 30ppm. This had an overriding effect over the other parameters. 10 ppm was found to be too low a dosage since the mass pull was very low, which resulted in poor reproducibility. It was, however, possible to get PGM grades as high as 1800 g/t, without substantial losses in recovery. At this range of frother concentrations, the effect would have been both in the pulp (change in bubble size) and in the froth (changing froth stability). CCC values of Dow 200 is about 20 ppm (Cho & Laskowski, 2002), which indicate that above 20 ppm there is no effect of additional frother on bubble size.

At a smaller range of frother concentration i: e 20 to 30 ppm, the frother concentration had no significant impact on PGM grade and recovery as well as mass pull. The frother concentration had an influence on water recovery (23% contribution to the regression equation), which, in turn, influences the mechanical entrainment of chromite and is reflected in an increased chrome grade and recovery. The chrome recovery has a linear dependency upon water recovery.

6.1.5 Interactive Effects of Factors

The main effects were dominant, but interactive effects were observed for most of the responses observed in this study. The interactive effects are most easily pictured in the 3-dimensional plots of the dependence of a response (for example PGM recovery) on two of the variables. Here it can be observed that the effect of one parameter may be different depending on the level of the second parameter. Thus, for example, chrome grade is significantly increased with increasing air flow at low depressant dosages, but hardly affected by air flow at high depressant dosages (Figure 4.38). This is important information for a control strategy.

6.2 Recommendations

While conducting this study certain points arose which should be addressed:

- During the commissioning of the column it was observed that at a high pulp density (30% solid) the pulp froth interface vanishes with an increase in superficial air velocity. This issue needs to be investigated in further research.

- The superficial air velocity is a dominant factor for all the responses. PGM recovery was found to increase with increasing superficial air velocity. However, it is known that, after a certain optimum level, the recovery may begin to decrease. This optimum level was not reached in this study and should be further investigated.

- The effects of froth height have not significant effect on chromite entrainment. This may due to the low range. The future research work must be carried out with high range of froth heights

- The change in collector dosage may give some interactive effects with other process parameters. So the collector dosage may be taken as a variable parameters for future study.

- These types of studies could be undertaken on plant scale due to the relatively small number of tests required.

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Appendix-A

Table 1 Constituents and their Mass for preparation of Synthetic Plant water (40L batch)

Constituents	**Formula**	**Mass(g)**
Magnesium Sulphate	$MgSO_4.7H_2O$	24.6
Magnesium Nitrate	$Mg(NO_3)_2.6H_2O$	4.28
Calcium Nitrate	$Ca(NO_3).4H_2O$	9.44
Calcium Chloride	$CaCl_2$	4.44
Sodium Chloride	$NaCl$	14.24
Sodium Carbonate	Na_2CO_3	1.2

Table 2 Results of the experiments at preliminary set of conditions

Froth Height	Superficial Air Velocity	Depressant dosage	Frother Conc.	Solid Rec	Water Rec	Solid Rec.%	Water Rec.%	Cr_2O_3 Grade	PGM Grade	Cr_2O_3 Rec.%	PGM Rec
cm	cm/sec	g/ton	ppm	g/min	g/min			%	gm./ton		
18	0.5	100	10	0.88	6.77	0.47	0.75	1.76	502	0.04	68
30	0.5	100	10	0.69	5.10	0.45	0.59	1.67	358	0.03	67
18	1.5	100	10	0.85	22.96	0.54	2.55	5.83	401	0.14	61
30	1.5	100	10	0.53	4.54	0.33	0.53	2.68	488	0.04	60
18	0.5	300	10	0.21	6.96	0.14	0.84	6.23	1701	0.04	60
30	0.5	300	10	0.29	8.66	0.19	1.06	4.20	1747	0.03	68
18	1.5	300	10	0.16	5.5	0.10	0.62	4.60	1750	0.02	67
30	1.5	300	10	0.52	40.78	0.31	4.59	8.99	699	0.14	73
24	1	200	20	1.02	100.17	0.85	11.10	6.73	459.01	0.19	70
18	0.5	100	30	4.98	195.03	3.27	23.68	10.63	74	1.48	68
30	0.5	100	30	2.33	104.66	1.50	12.32	5.74	170	0.38	66
18	1.5	100	30	9.60	374.20	5.87	44.21	12.85	48	3.31	71
30	1.5	100	30	5.65	224.55	3.33	26.27	12.32	110	1.87	70
18	0.5	300	30	3.80	194.54	2.64	23.90	14.63	100	1.57	69
30	0.5	300	30	3.80	189.72	2.35	22.10	15.61	102	1.70	68
18	1.5	300	30	6.15	297.82	4.15	36.06	14.14	96	2.48	72
30	1.5	300	30	4.31	136.48	2.71	15.93	13.00	123	0.58	69

Table 3 Results of the experiments at 20 and 30 ppm frother concentrations

Froth Heig	Superficia	Depressar	Frother co	Solid Rec	Water Rec	Solid Rec	Water Rec	Cr2O3 Rec	Cr2O3 Gra	PGM Rec	PGM Grade
cm	cm/sec	g/ton	ppm	%	%	g/min	g/min	g/min	%	%	g/t
18	0.5	100	20	1.9	10.78	3	99	0.2	8	69	135
30	0.5	100	20	0.6	2.74	1.08	27	0.05	4	66	300
18	1.5	100	20	5.9	30.82	7.28	206	0.9	12	72	50
30	1.5	100	20	4.3	23.46	5.4	162	0.8	11	70	80
18	0.5	300	20	1.4	9.85	2.23	82	0.3	12	69	171
30	0.5	300	20	0.8	2.21	1.35	19	0.2	12	69	326
18	1.5	300	20	5.7	34.75	6.9	232	1	15	70	40
30	1.5	300	20	4.3	29.29	5.35	202	0.9	12	69	93
18	0.5	100	30	3.3	23.68	4.98	195	0.5	11	68	74
30	0.5	100	30	1.5	12.32	2.33	105	0.1	6	66	170
18	1.5	100	30	5.9	44.21	9.6	374	1.2	13	71	48
30	1.5	100	30	3.3	26.27	5.65	225	0.7	12	70	110
18	0.5	300	30	2.6	23.9	3.8	195	0.6	15	69	100
30	0.5	300	30	2.4	22.1	3.8	190	0.6	16	68	102
18	1.5	300	30	4.2	36.06	6.15	298	1.2	14	72	96
30	1.5	300	30	2.7	15.93	4.31	136	0.6	13	69	123

Appendix-B

Response of solid recovery

Table B1 ANOVA model for solid recovery

Source model	Sum of Squares	df	Mean Square	F value	P value Prob>F	Significance
Model	66.73	3	22.24	20.17	< 0.0001	Significant
Froth Height-A	13.45	1	13.45	12.19	0.0044	
Superficial air velocity-B	49.25	1	49.25	44.65	< 0.0001	
Frother Conc-C	4.03	1	4.03	3.65	0.0801	
Residual	13.24	12	1.10			
Cor Total	79.96	15				

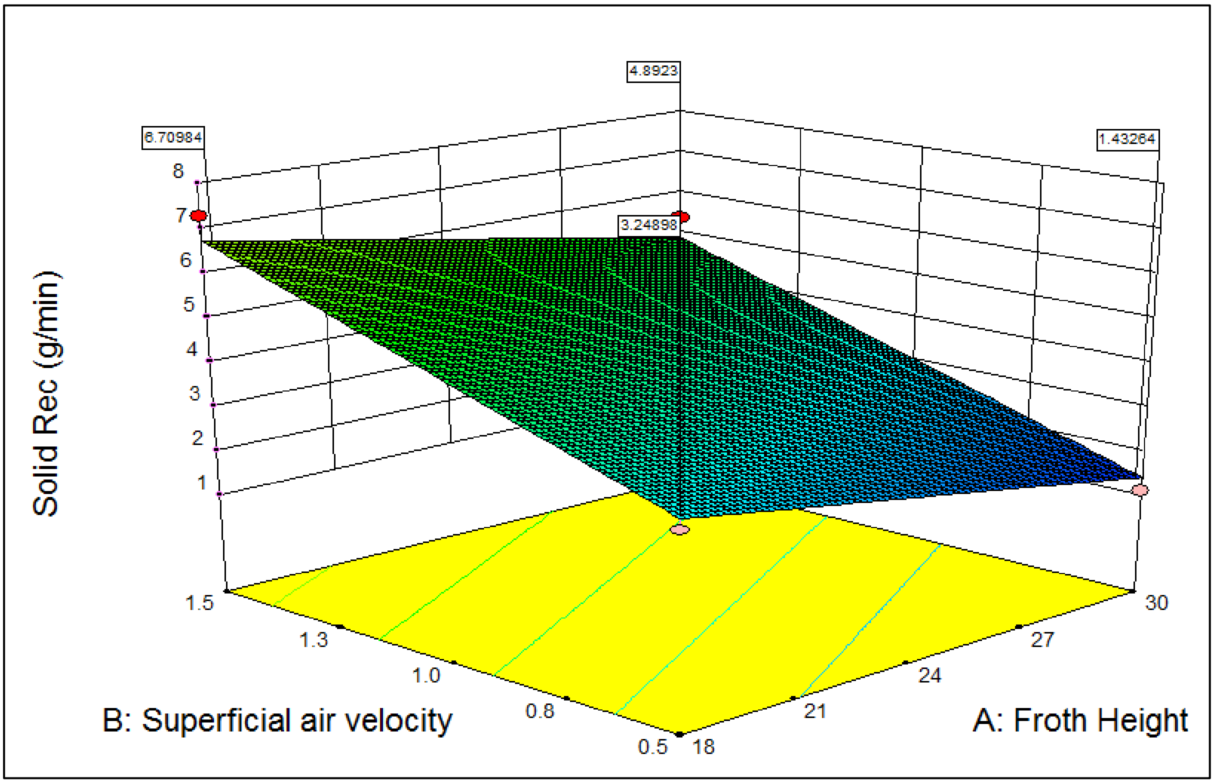


Figure B1 Effect of superficial air velocity and froth height on solids recovery keeping other factors at low levels (100g/t depressant and 20ppm frother)

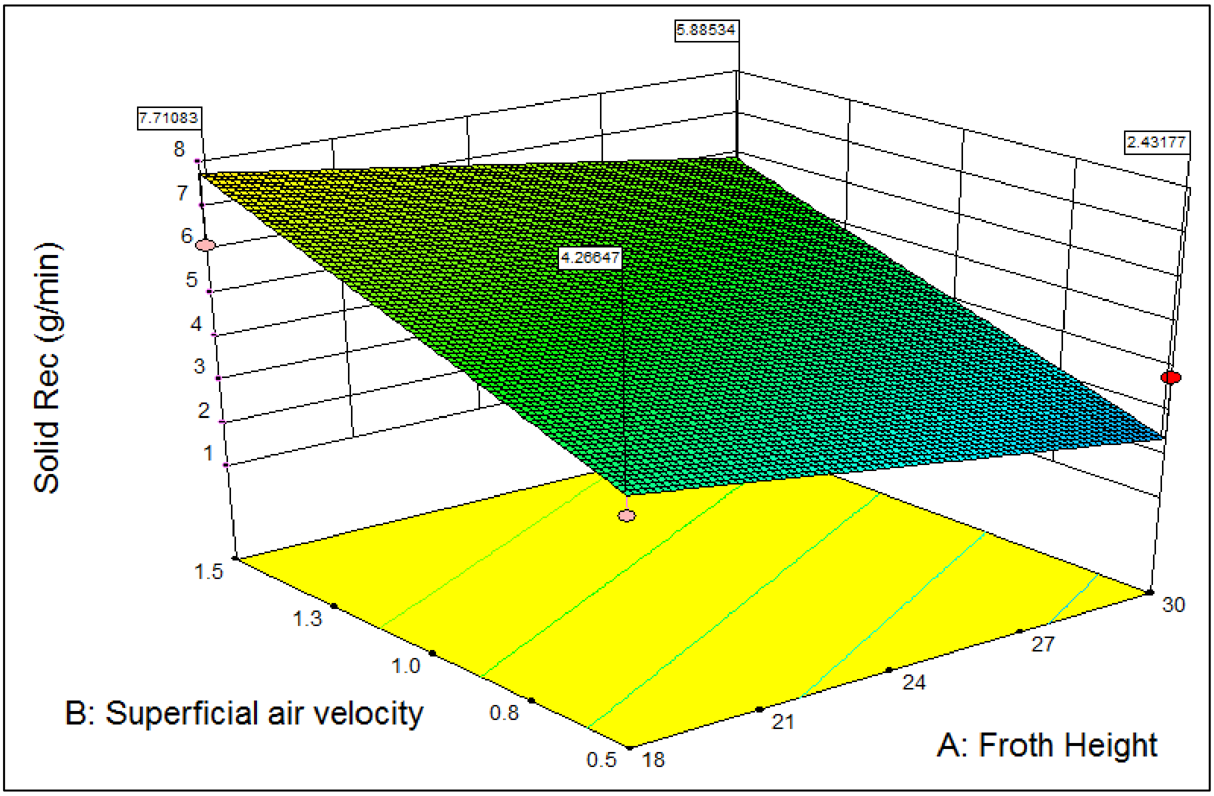


Figure B2 Effect of superficial air velocity and froth height on solids recovery keeping other factors at high levels (300g/t depressant and 30ppm frother)

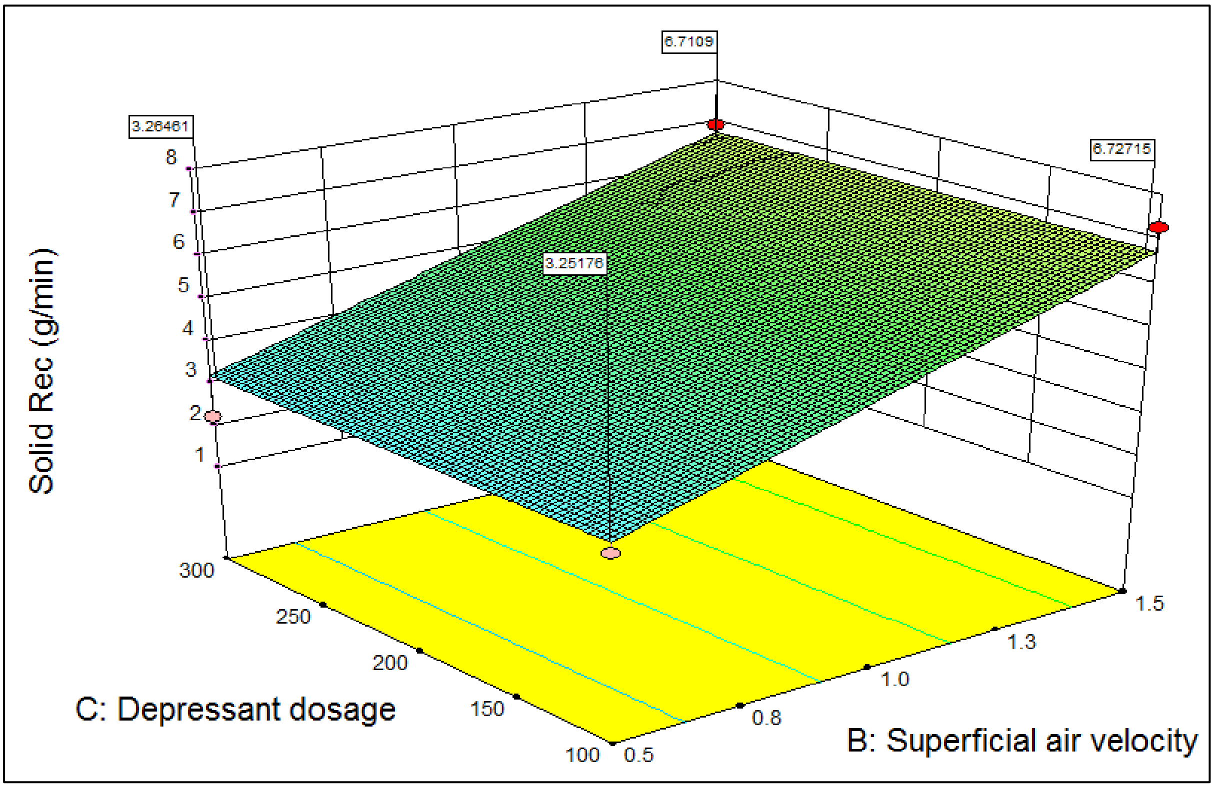


Figure B3 Effect of superficial air velocity and depressant dosage on solid recovery keeping other factors at low levels (18 cm froth height and 20ppm frother)

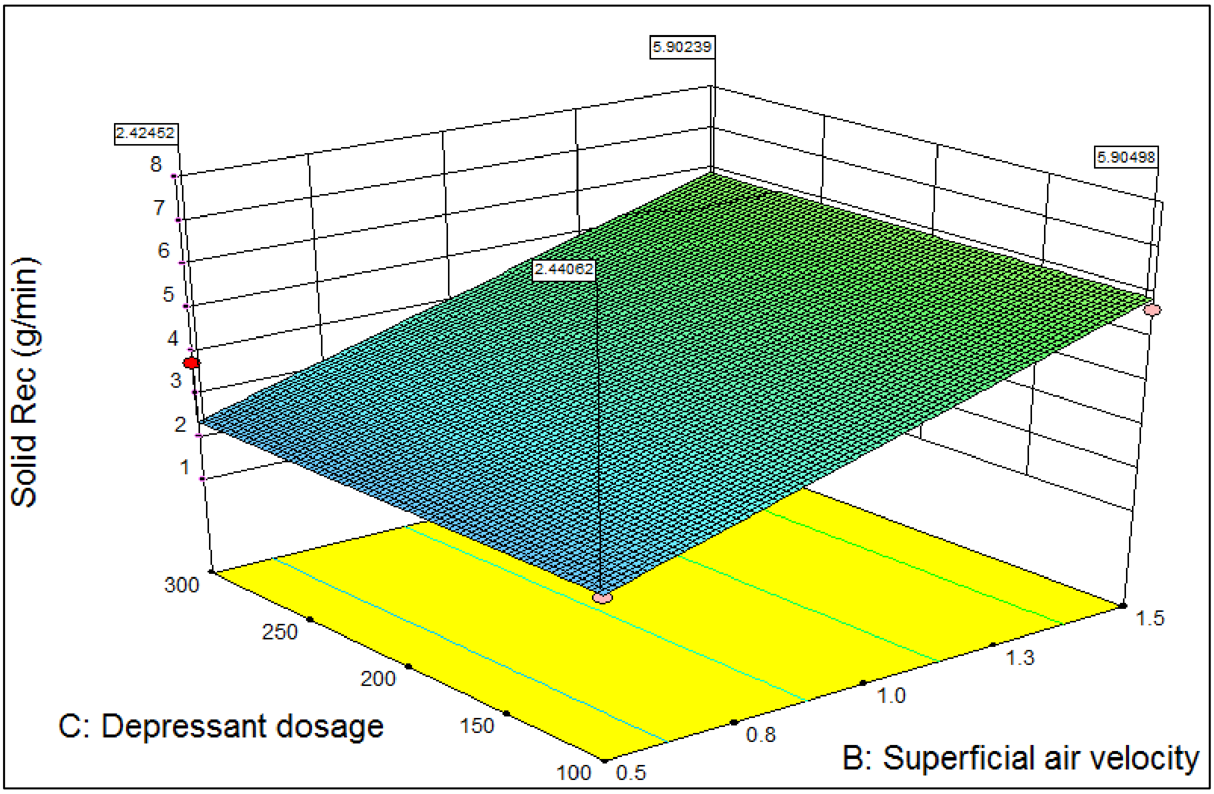


Figure B4 Effect of superficial air velocity and depressant dosage on solid recovery keeping other factors at high levels (30 cm froth height and 30ppm frother)

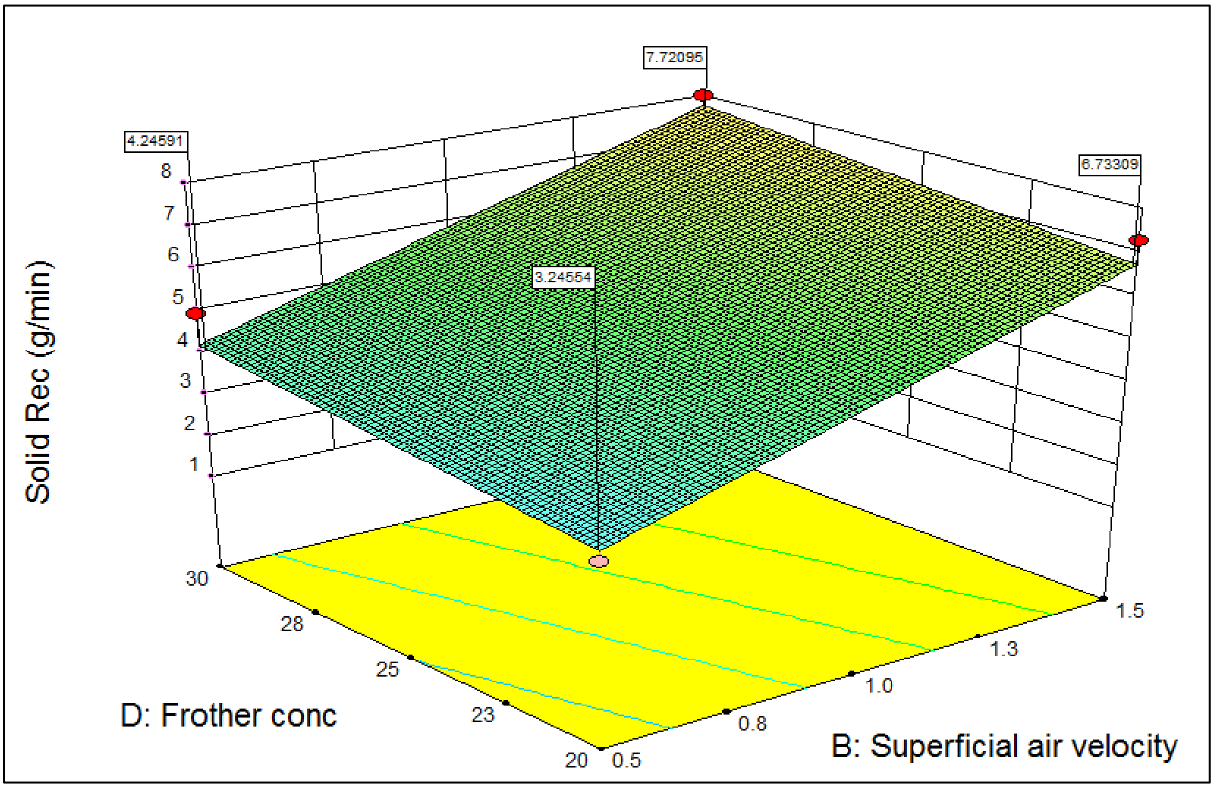


Figure B5 Effect of superficial air velocity and frother concentration on solid recovery keeping other factors at low levels (18 cm froth height and 100g/t depressant)

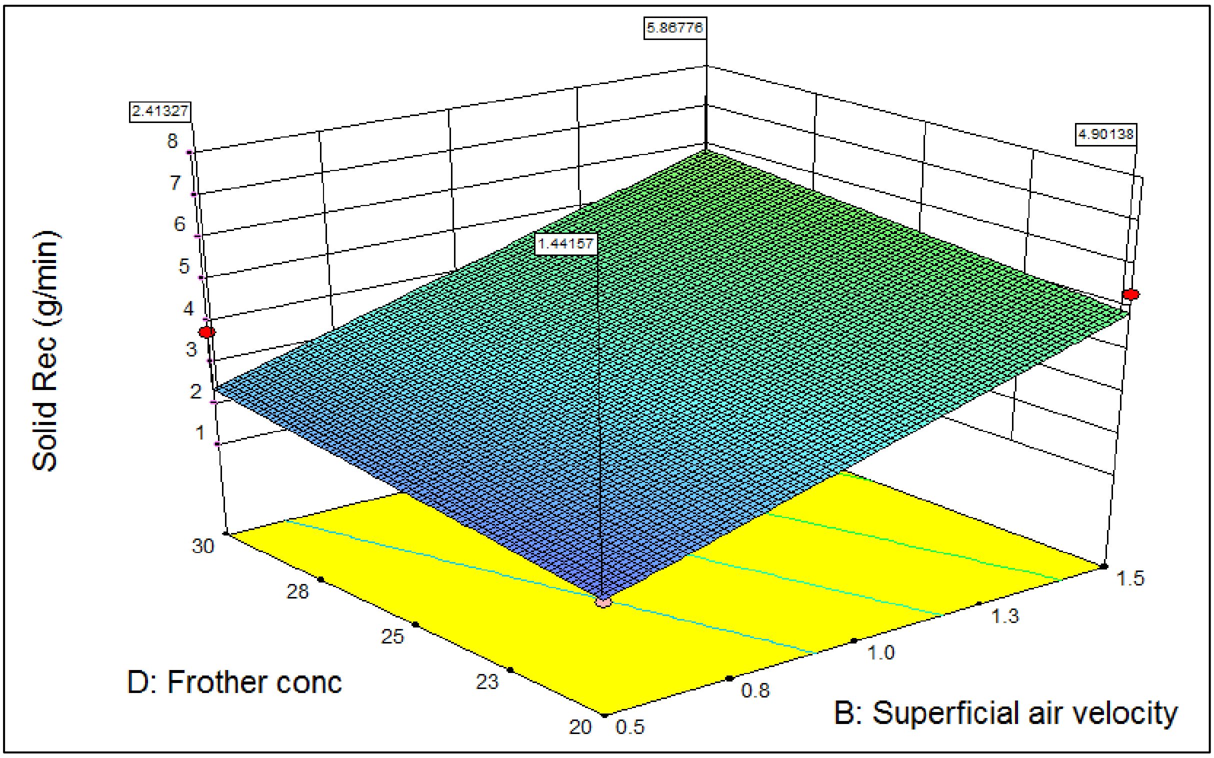


Figure B6 Effect of superficial air velocity and Frother concentration on solid recovery keeping other factors at high levels (30 cm froth height and 300g/t depressant)

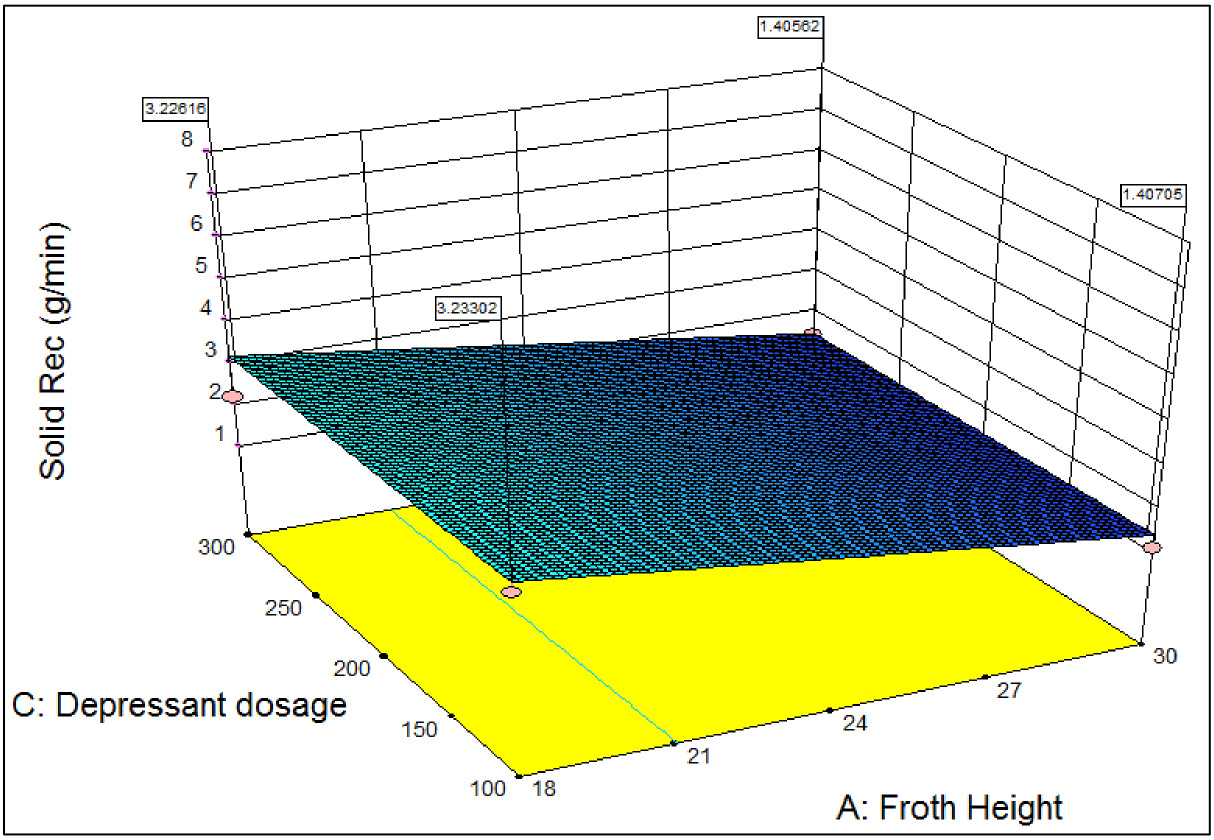


Figure B7 Effect of froth height and depressant dosage on solid recovery keeping other factors at low levels (0.5 cm/sec superficial air velocity and 20ppm frother concentration)

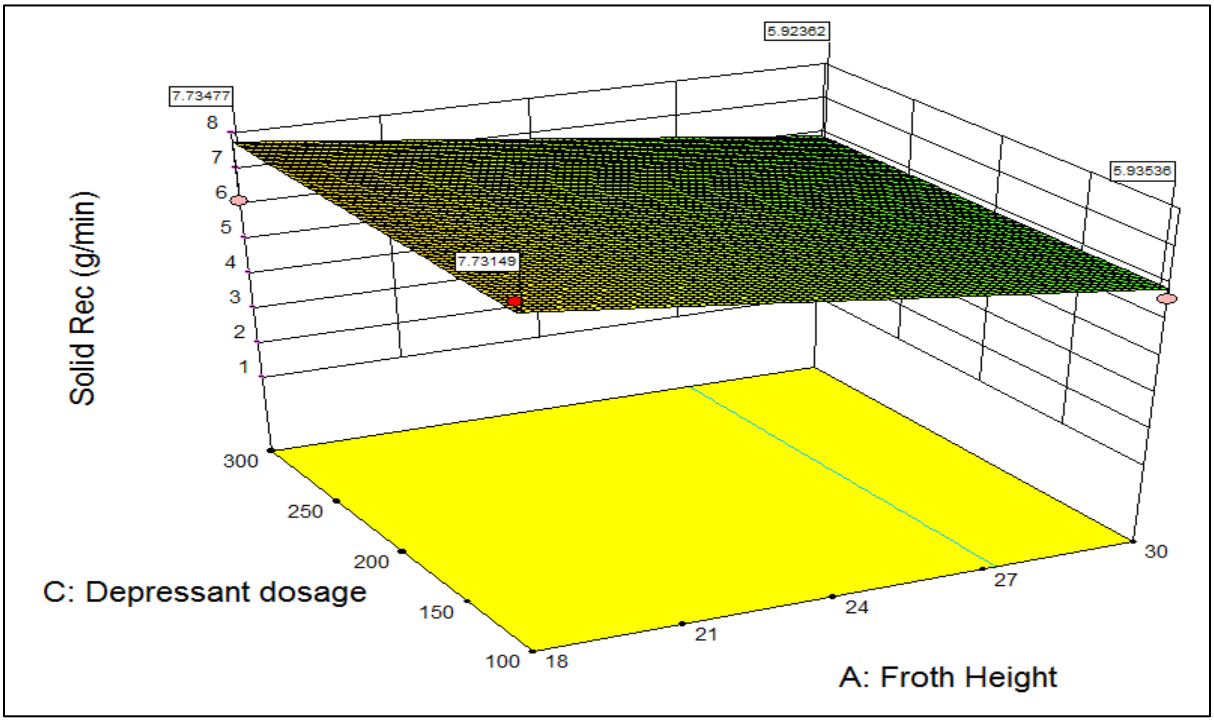


Figure B8 Effect of froth height and depressant dosage on solid recovery keeping other factors at high levels (1.5 cm/sec superficial air velocity and 30ppm frother concentration)

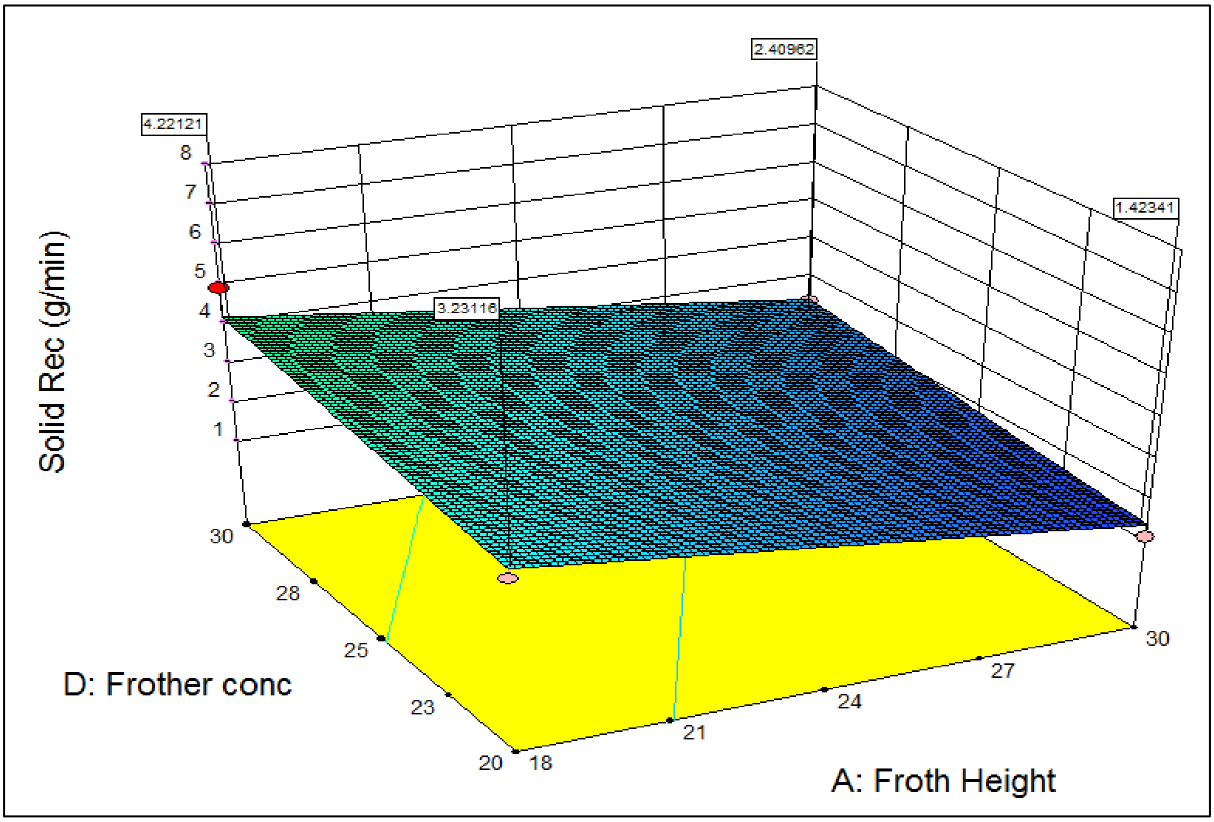


Figure B9 Effect of froth height and frother concentration on solid recovery keeping other factors at low levels (0.5 cm/sec superficial air velocity and 100g/t depressant dosage)

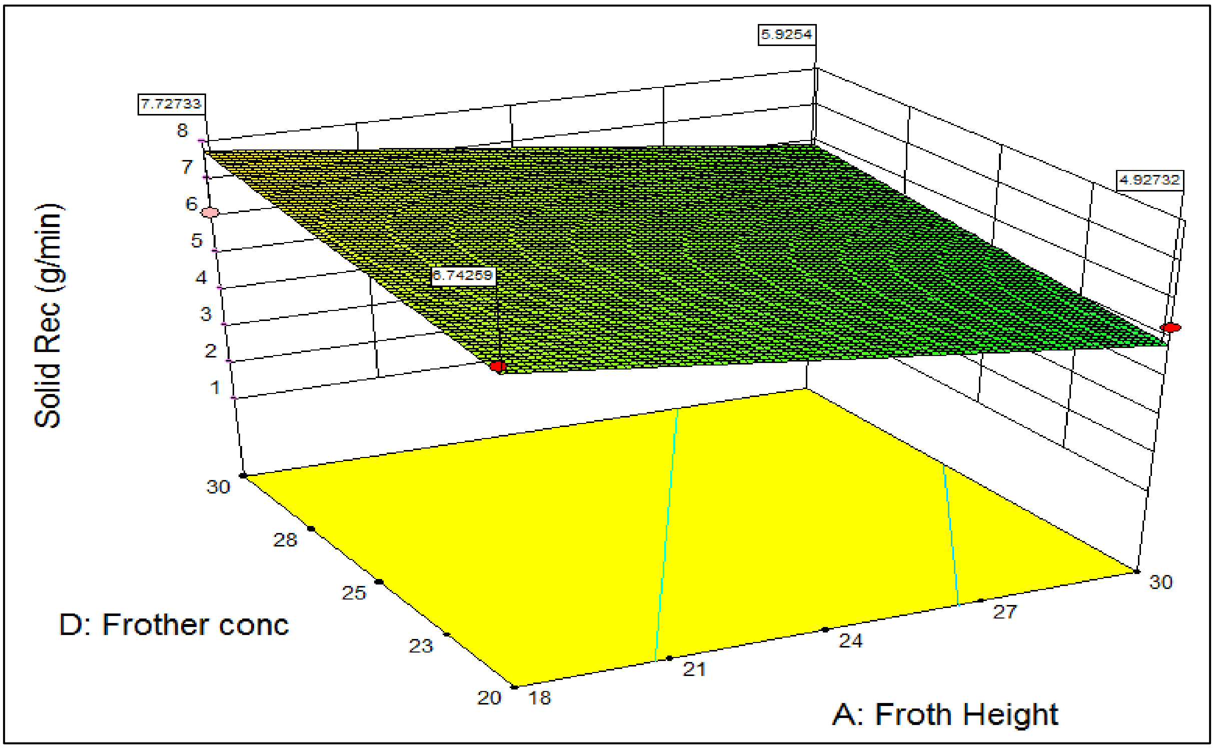
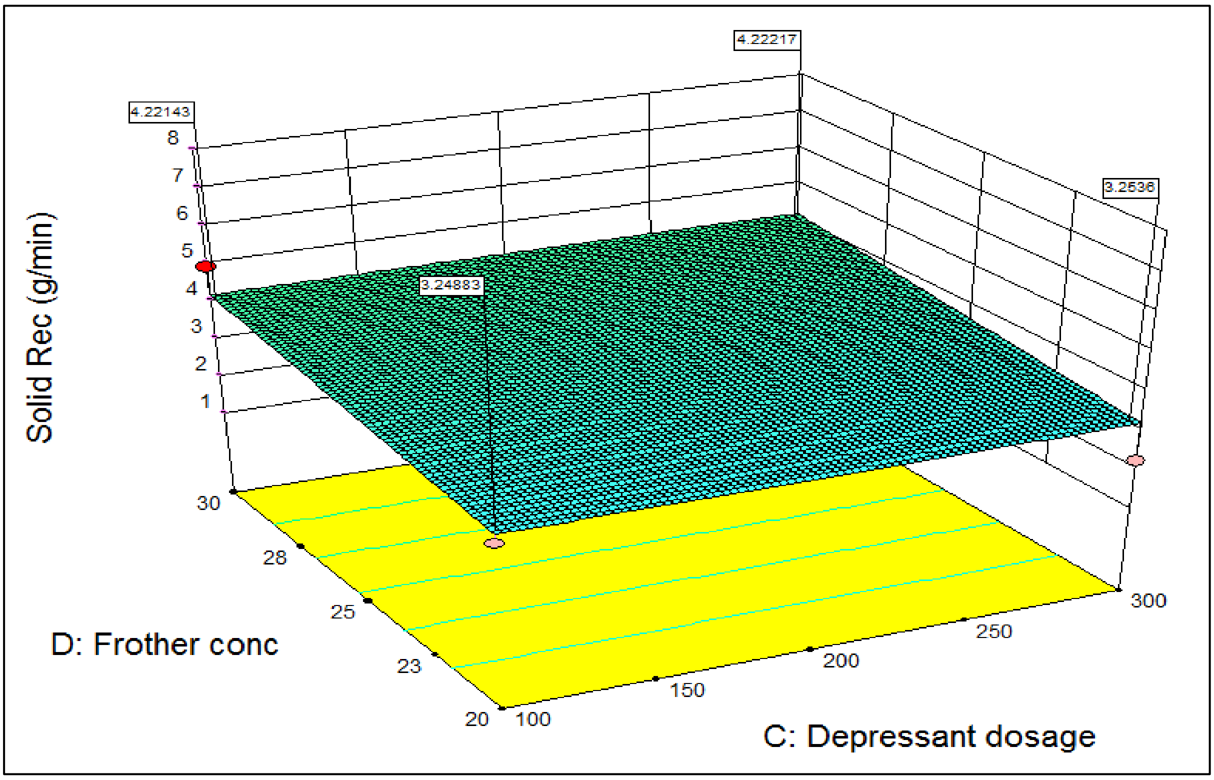
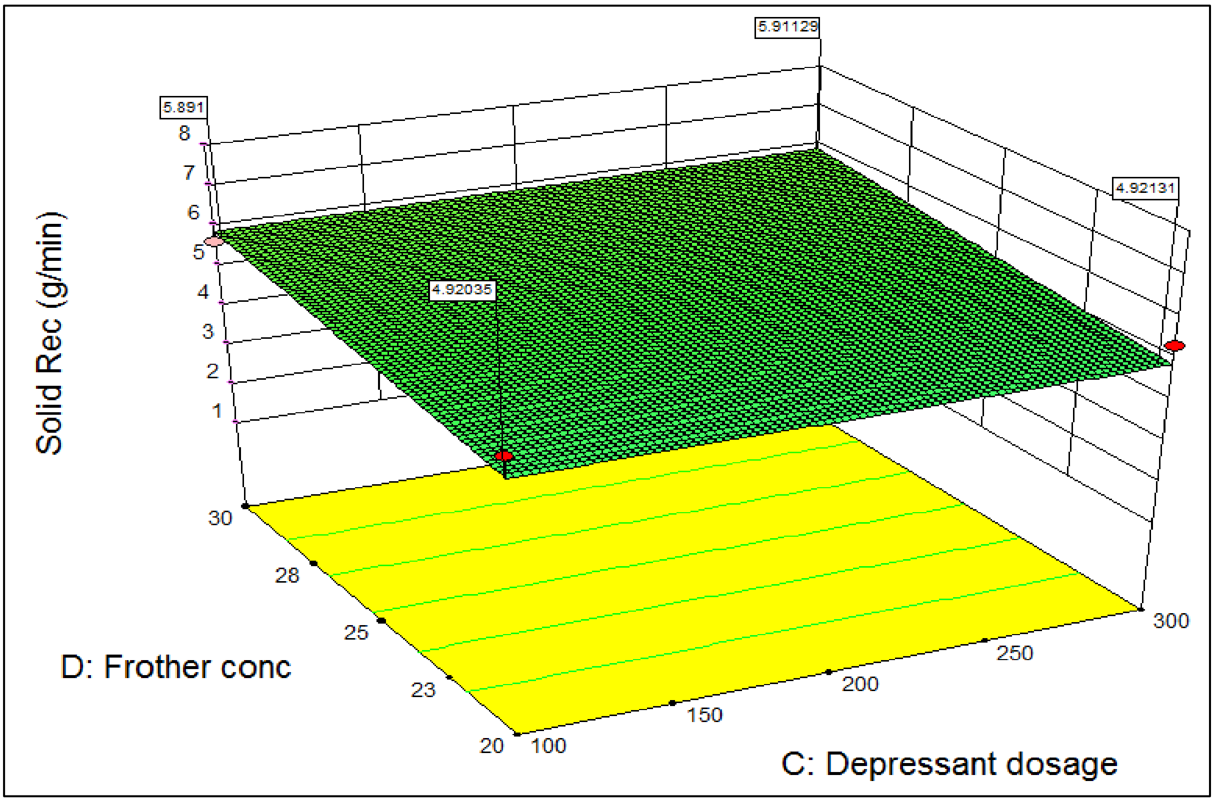


Figure B10 Effect of froth height and frother concentration on solid recovery keeping other factors at high levels (1.5 cm/sec superficial air velocity and 300g/t depressant dosage)



B11 Effect of frother concentration and depressant dosage on solid recovery keeping other factors at low levels (0.5 cm/sec superficial air velocity and 18 cm froth height)



B12 Effect of frother concentration and depressant dosage on solid recovery keeping other factors at high levels (1.5 cm/sec superficial air velocity and 30 cm froth height)

Appendix-C

Response of Water Recovery

Table C1 ANOVA model for water recovery

Source model	Sum of Squares	df	Mean Square	F value	P value Prob>F	Significance
Model	113900	4	28478.52	19.10	0.0001	Significant
Froth Height-A	23684.83	1	23684.83	15.89	0.0021	
Superficial air velocity-B	53368.51	1	53368.51	35.80	0.0001	
Frother conc-D	29630.03	1	29630.03	19.88	0.0010	
BCD	7230.74	1	7230.74	4.85	0.0499	
Residual	16397.55	11	1490.69			
Cor Total	130300	15				

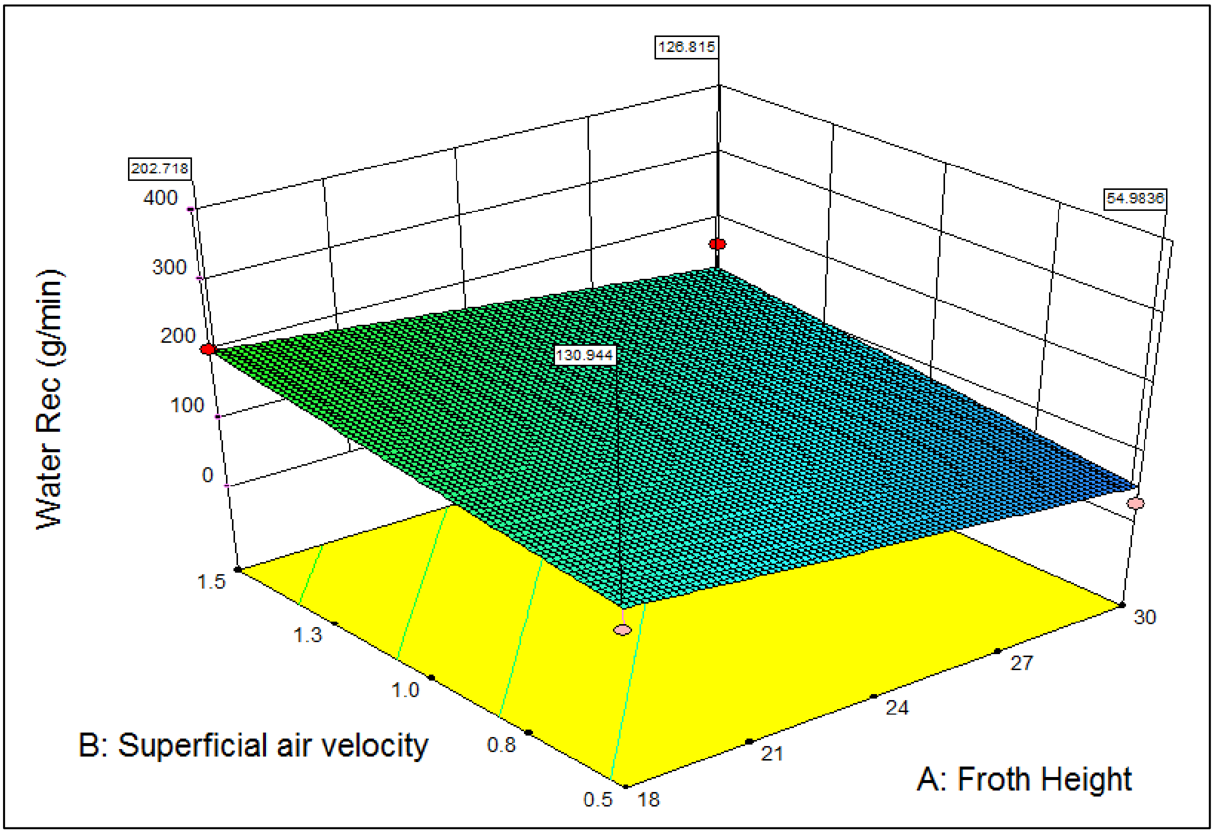


Figure C1 Effect of superficial air velocity and froth height on water recovery keeping other factors at low levels (100g/t depressant and 20ppm frother)

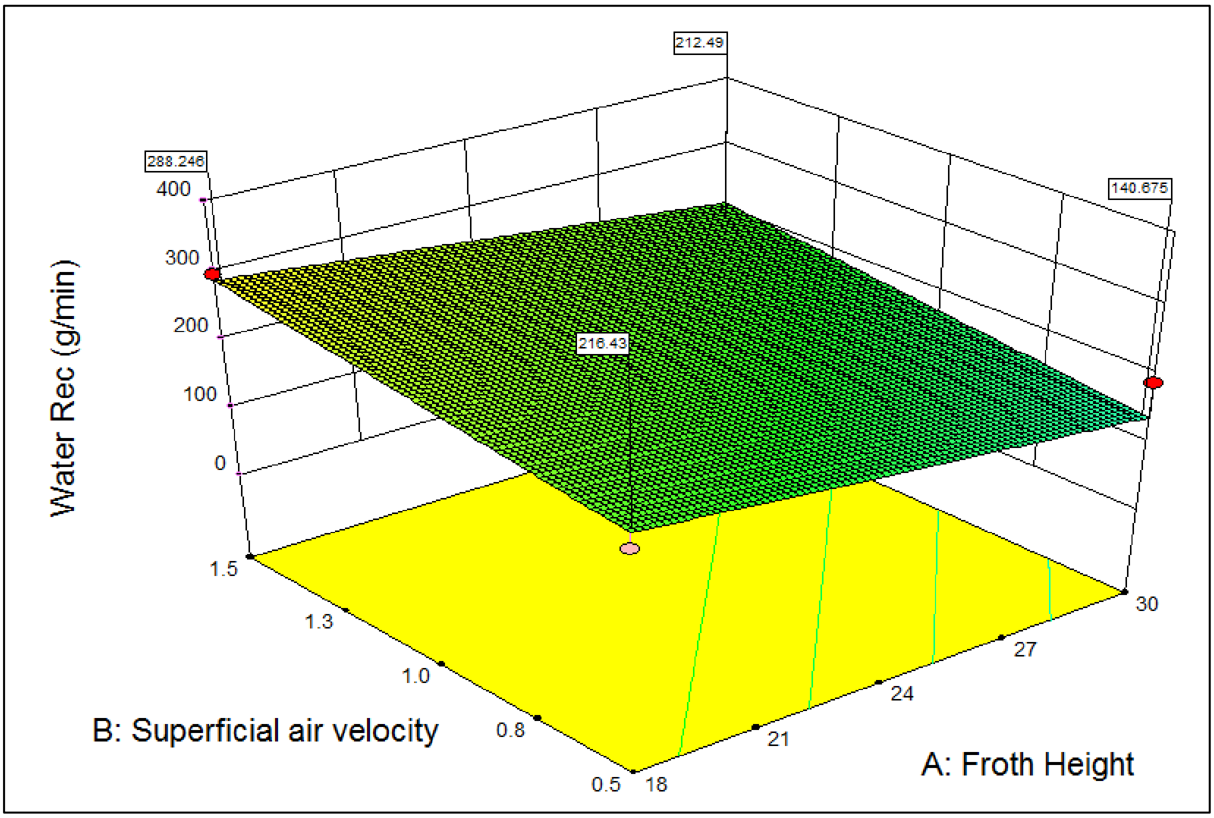


Figure C2 Effect of superficial air velocity and froth height on water recovery keeping other factors at high levels (300g/t depressant and 30ppm frother)

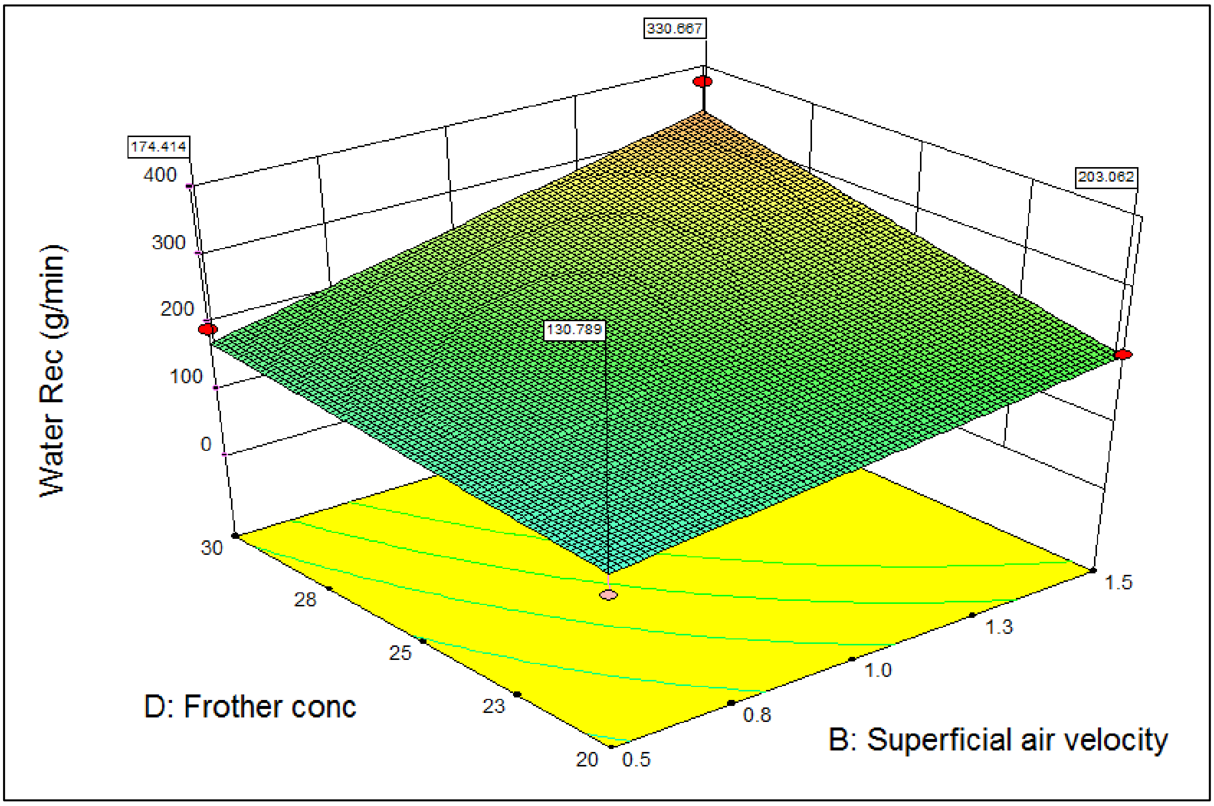


Figure C3 Effect of superficial air velocity and frother concentration on water recovery keeping other factors at low levels (18 cm froth height and 100g/t depressant)

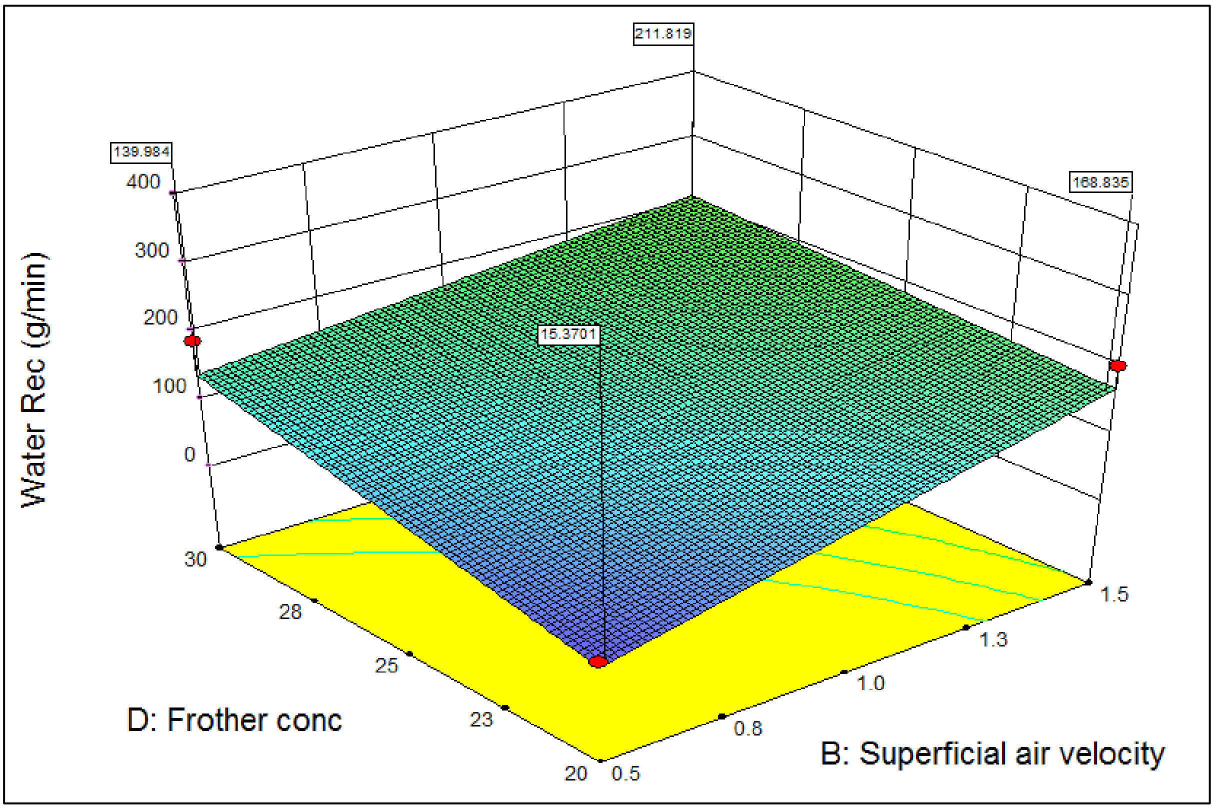


Figure C4 Effect of superficial air velocity and frother concentration on water recovery keeping other factors at high levels (30 cm froth height and 300g/t depressant)

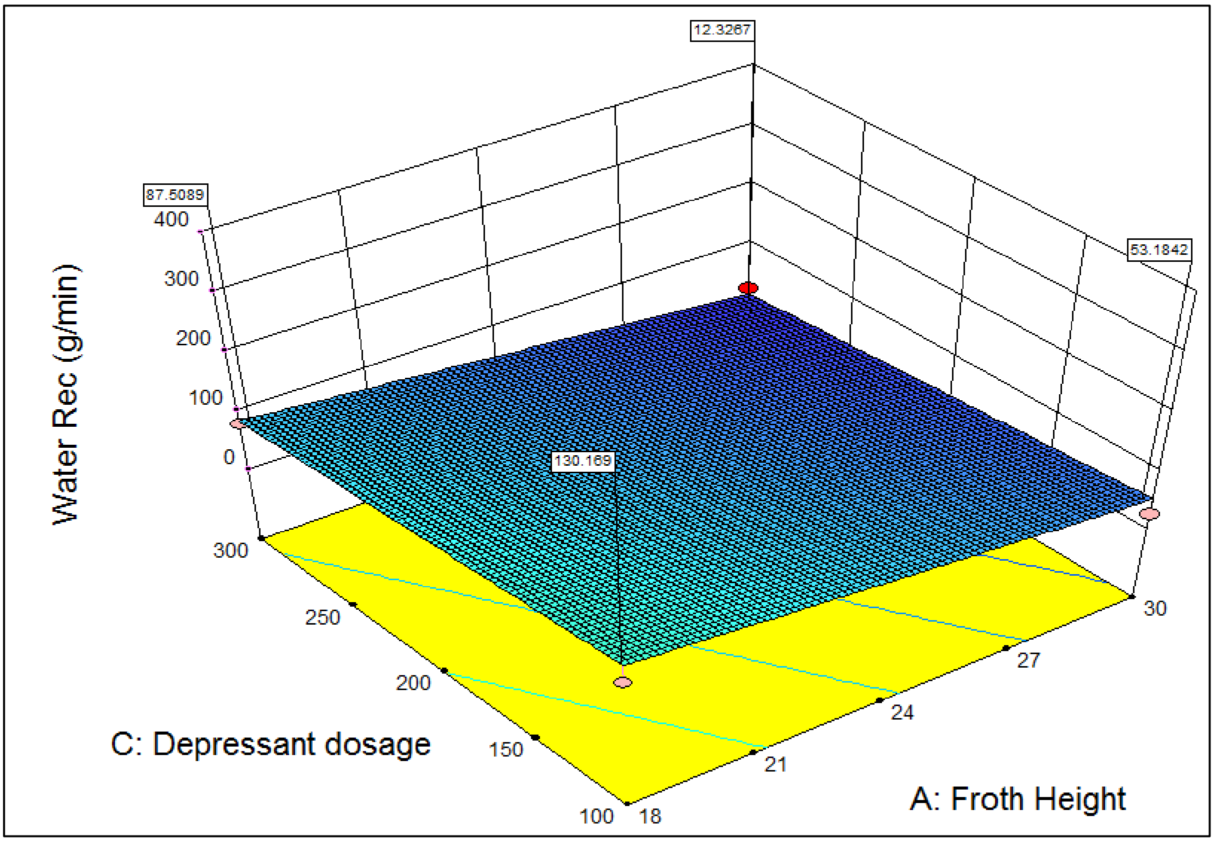


Figure C5 Effect of froth height and depressant dosage on water recovery keeping other factors at low levels (0.5 cm/sec superficial air velocity and 20ppm frother concentration)

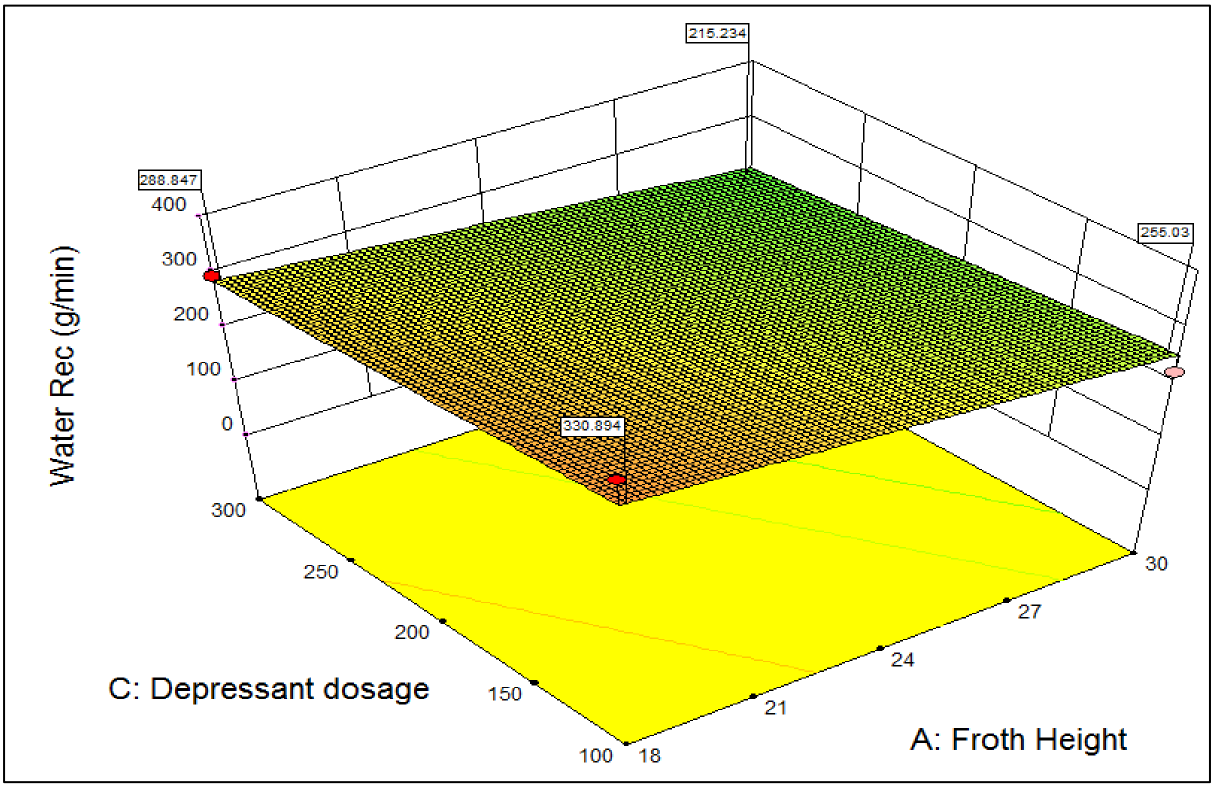


Figure C6 Effect of froth height and depressant dosage on water recovery keeping other factors at high levels (1.5 cm/sec superficial air velocity and 30ppm frother concentration)

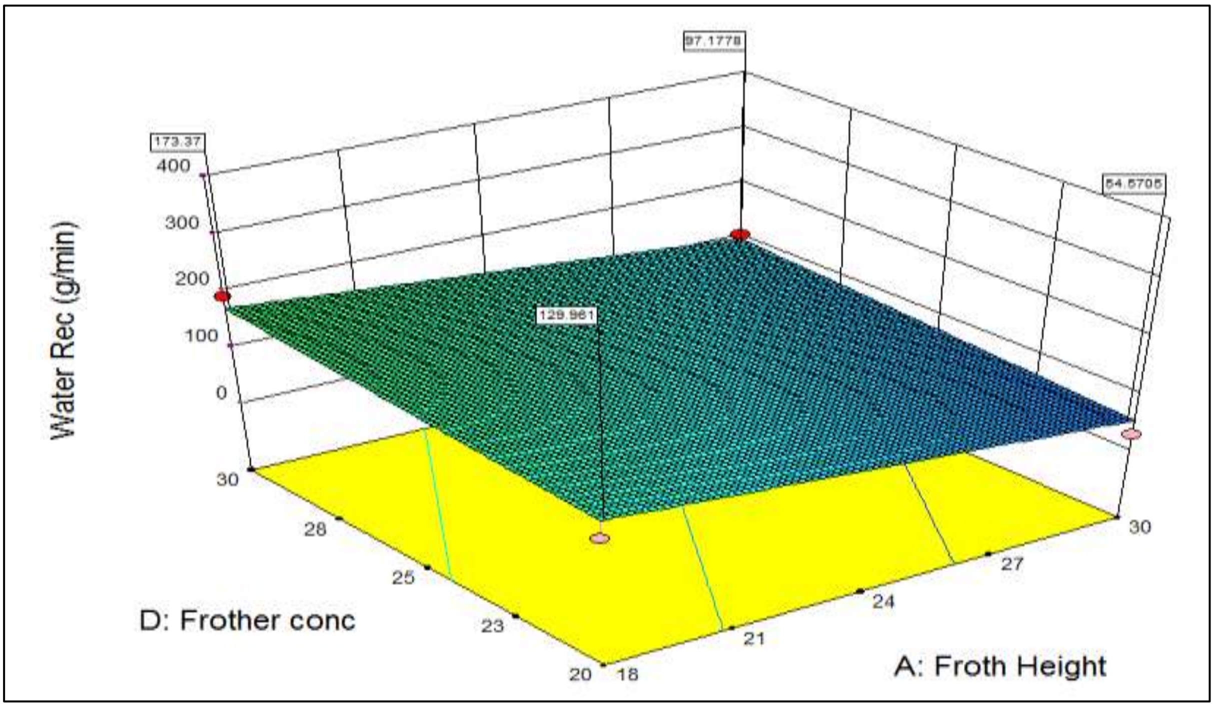


Figure C7 Effect of froth height and frother concentration on water recovery keeping other factors at low levels (0.5 cm/sec superficial air velocity and 100g/t depressant)

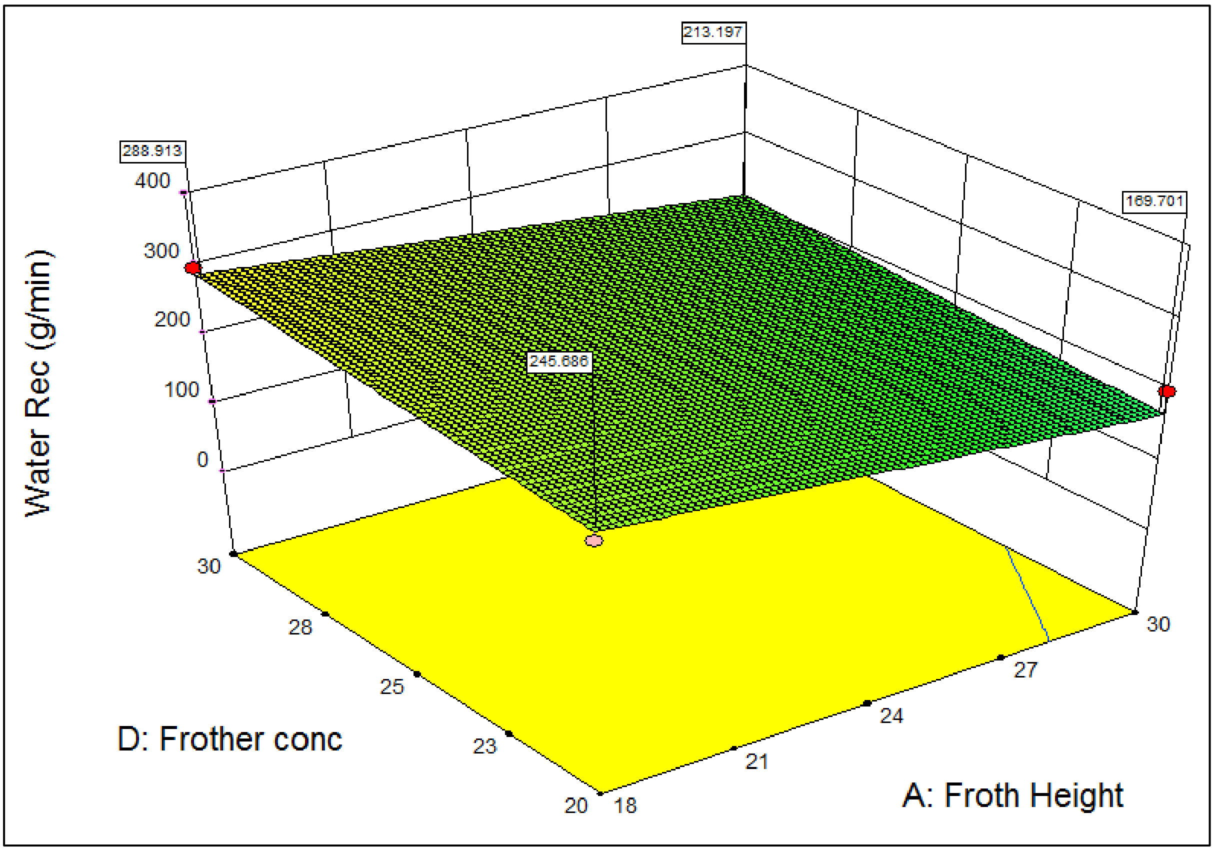


Figure C8 Effect of froth height and frother concentration on water recovery keeping other factors at high levels (1.5 cm/sec superficial air velocity and 300g/t depressant)

Appendix-D

Response of Chrome Recovery

Table D1 ANOVA model for chrome recovery

Source model	Sum of Squares	df	Mean Square	F value	P value Prob>F	Significance
Model	1.83	3	0.61	21.53	0.0001	Significant
Froth Height-A	0.28	1	0.28	9.88	0.0085	
Superficial air velocity-B	1.46	1	1.46	51.37	0.0001	
D-Frother conc	0.095	1	0.095	3.34	0.0927	
Residual	0.34	12	0.028			
Cor Total	2.18	15				

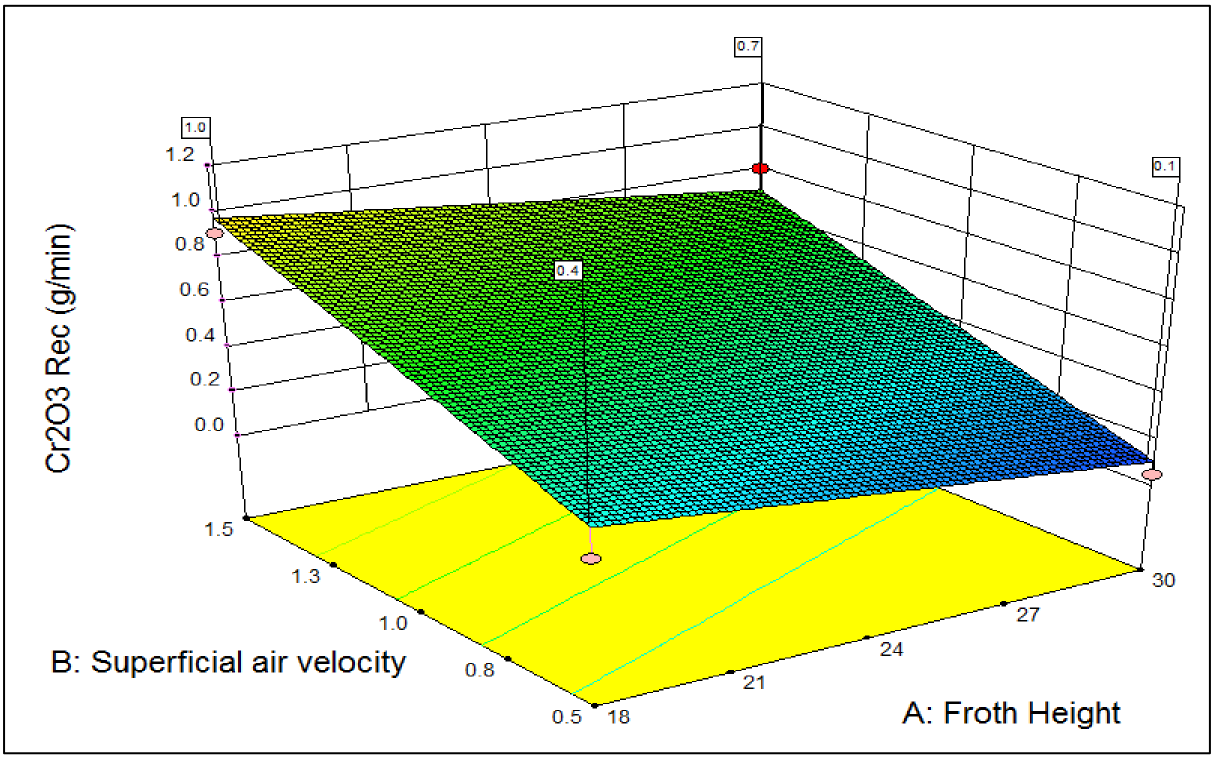


Figure D1 Effect of superficial air velocity and froth height on chrome recovery keeping other factors at low levels (100g/t depressant and 20ppm frother)

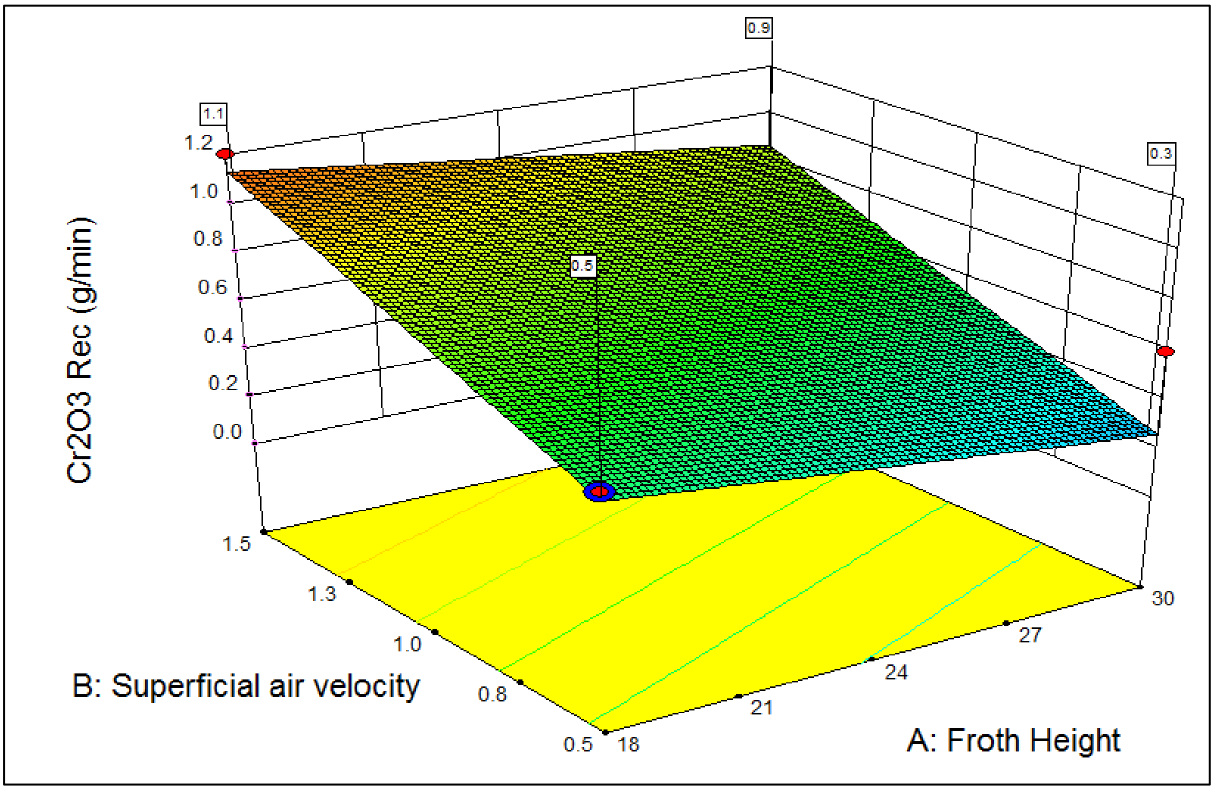


Figure D2 Effect of superficial air velocity and froth height on chrome recovery keeping other factors at high levels (300g/t depressant and 30ppm frother)

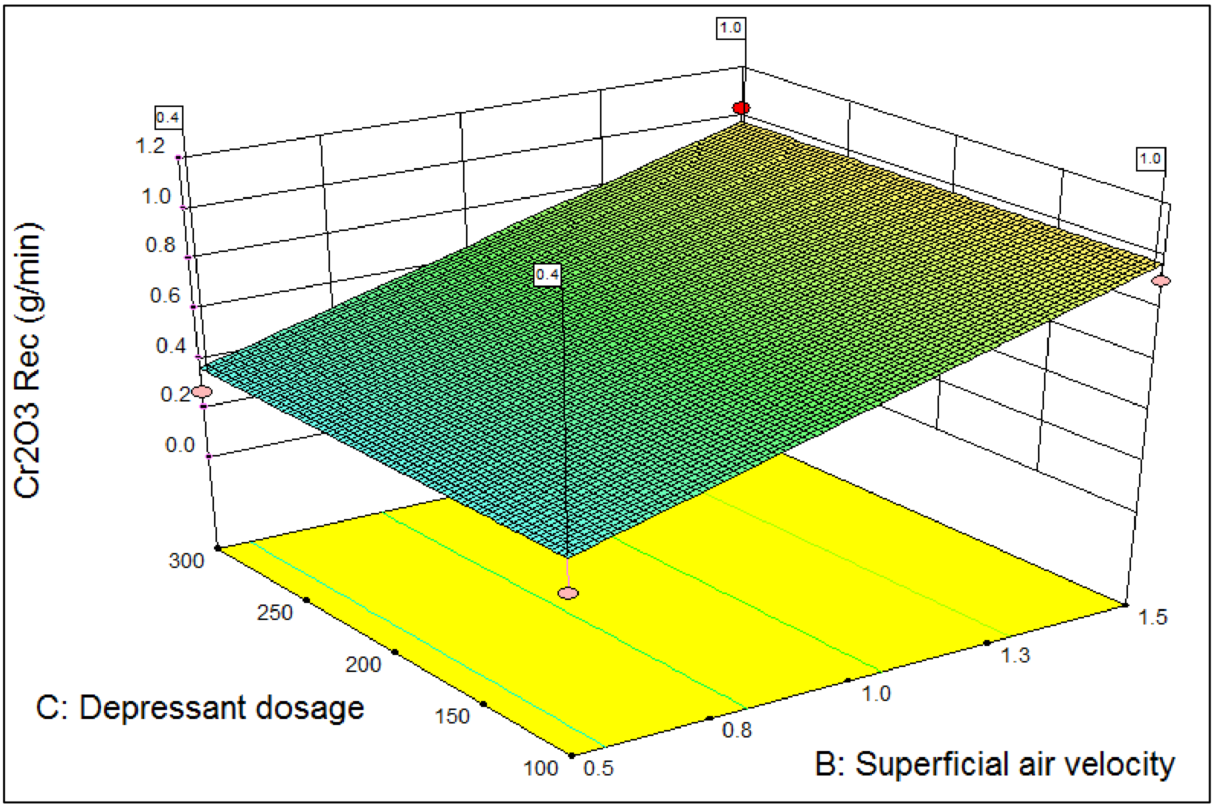


Figure D3 Effect of superficial air velocity and depressant dosage on chrome recovery keeping other factors at low levels (18cm froth height and 20ppm frother)

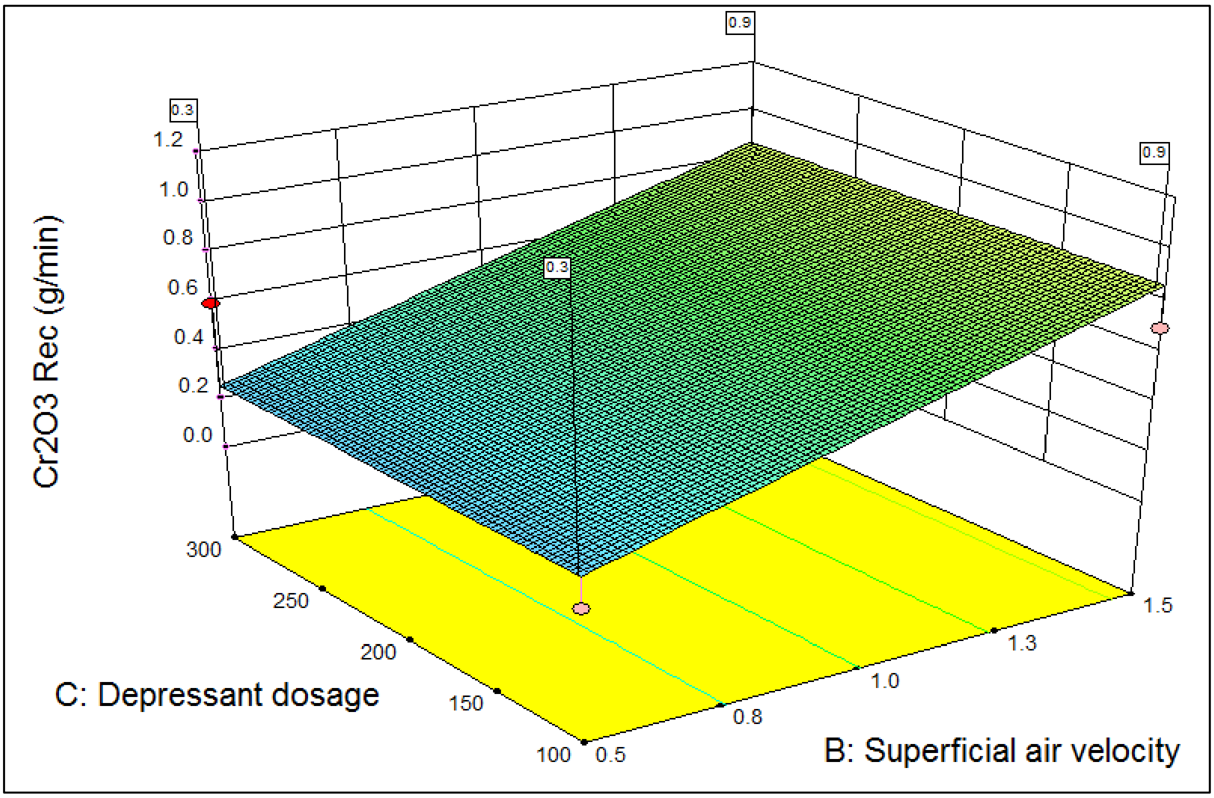


Figure D4 Effect of superficial air velocity and depressant dosage on chrome recovery keeping other factors at high levels (30cm froth height and 30ppm frother)

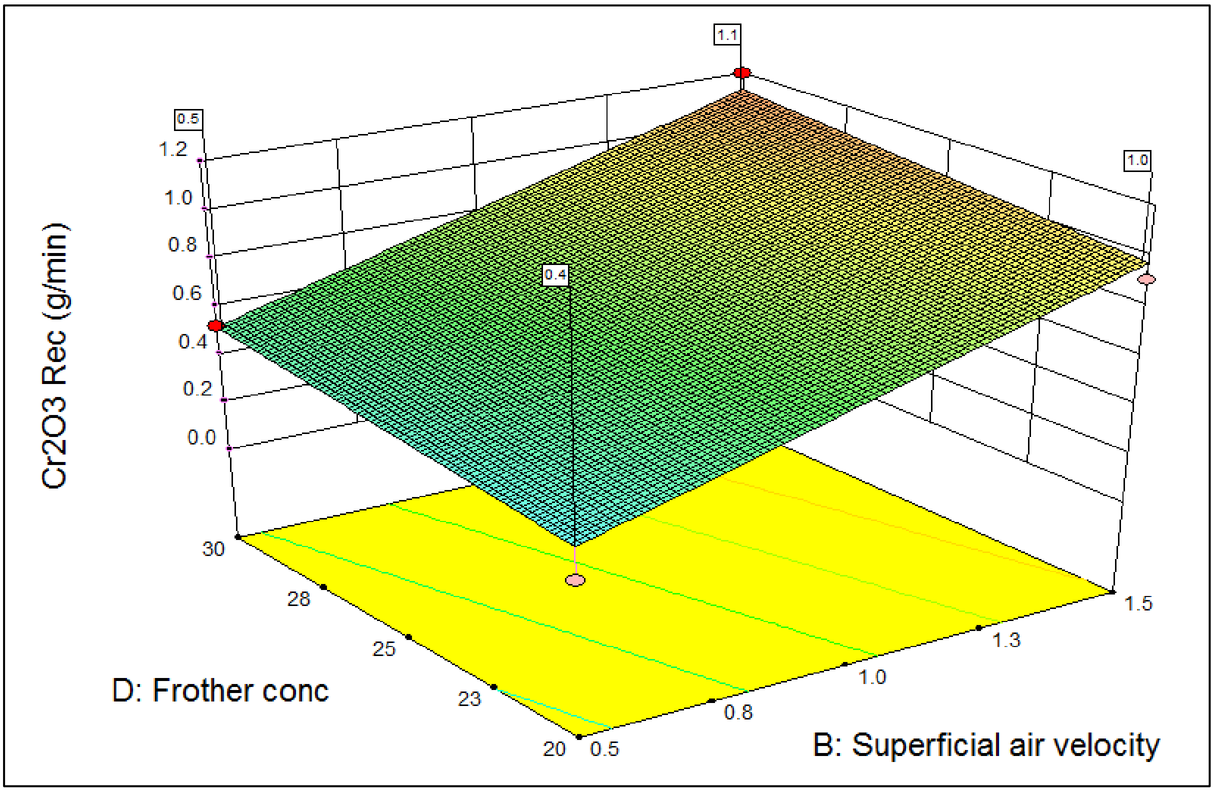


Figure D5 Effect of superficial air velocity and frother concentration on chrome recovery keeping other factors at low levels (18cm froth height and 100g/t depressant)

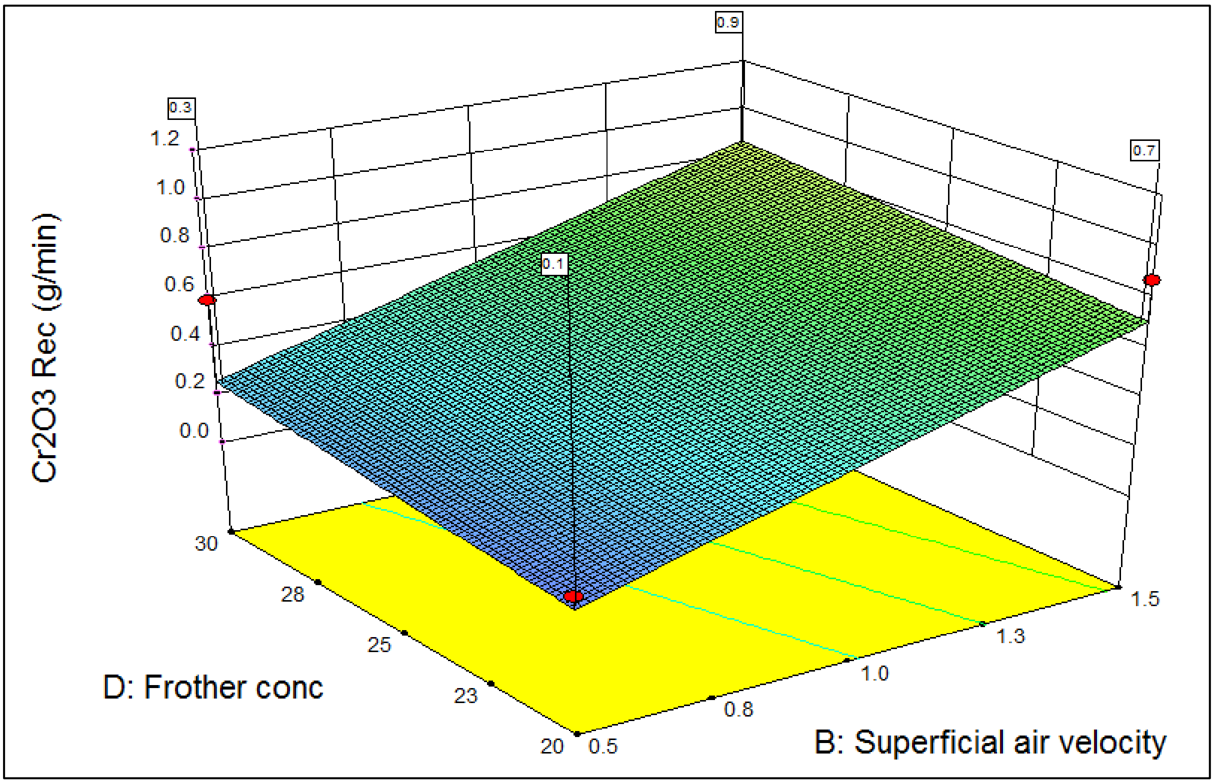


Figure D6 Effect of superficial air velocity and frother concentration on chrome recovery keeping other factors at high levels (30cm froth height and 300g/t depressant)

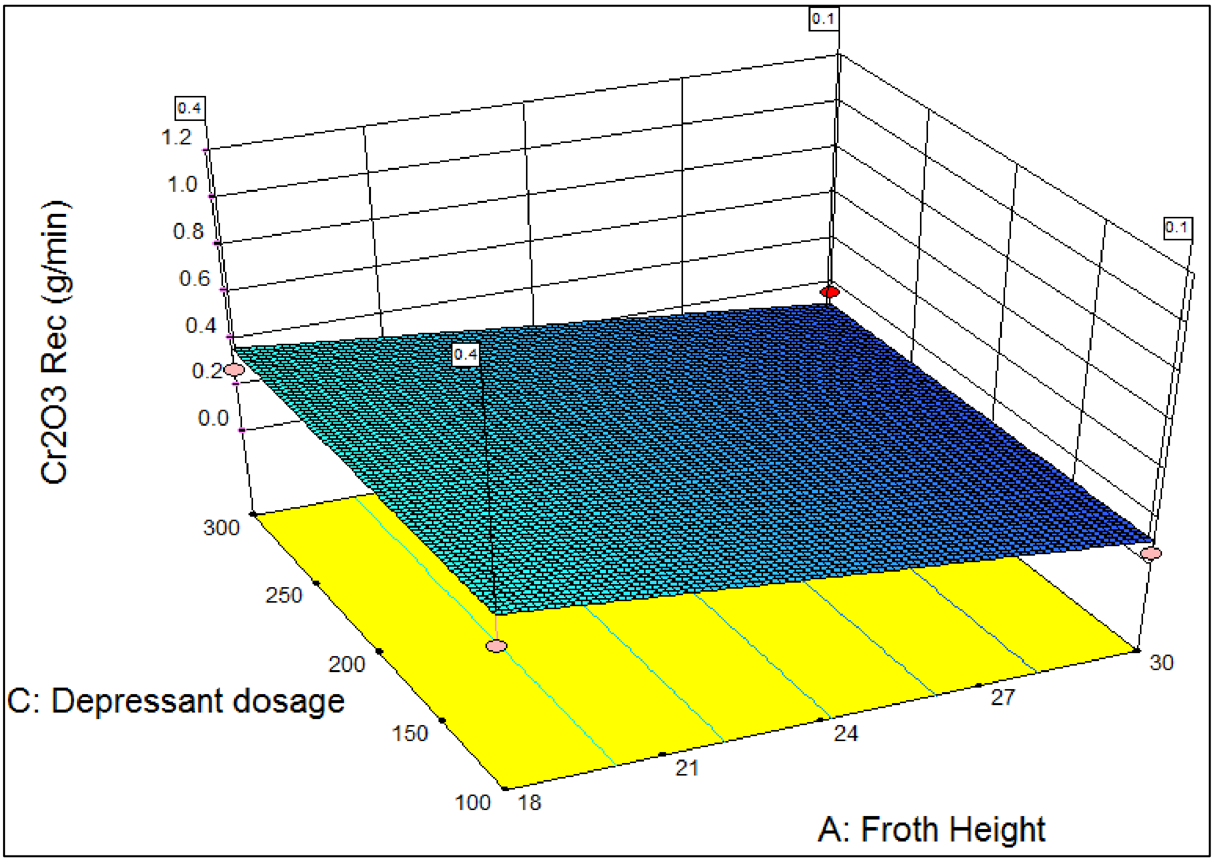


Figure D7 Effect of froth height and depressant dosage on chrome recovery keeping other factors at low levels (0.5cm/sec superficial air velocity and 20ppm frother)

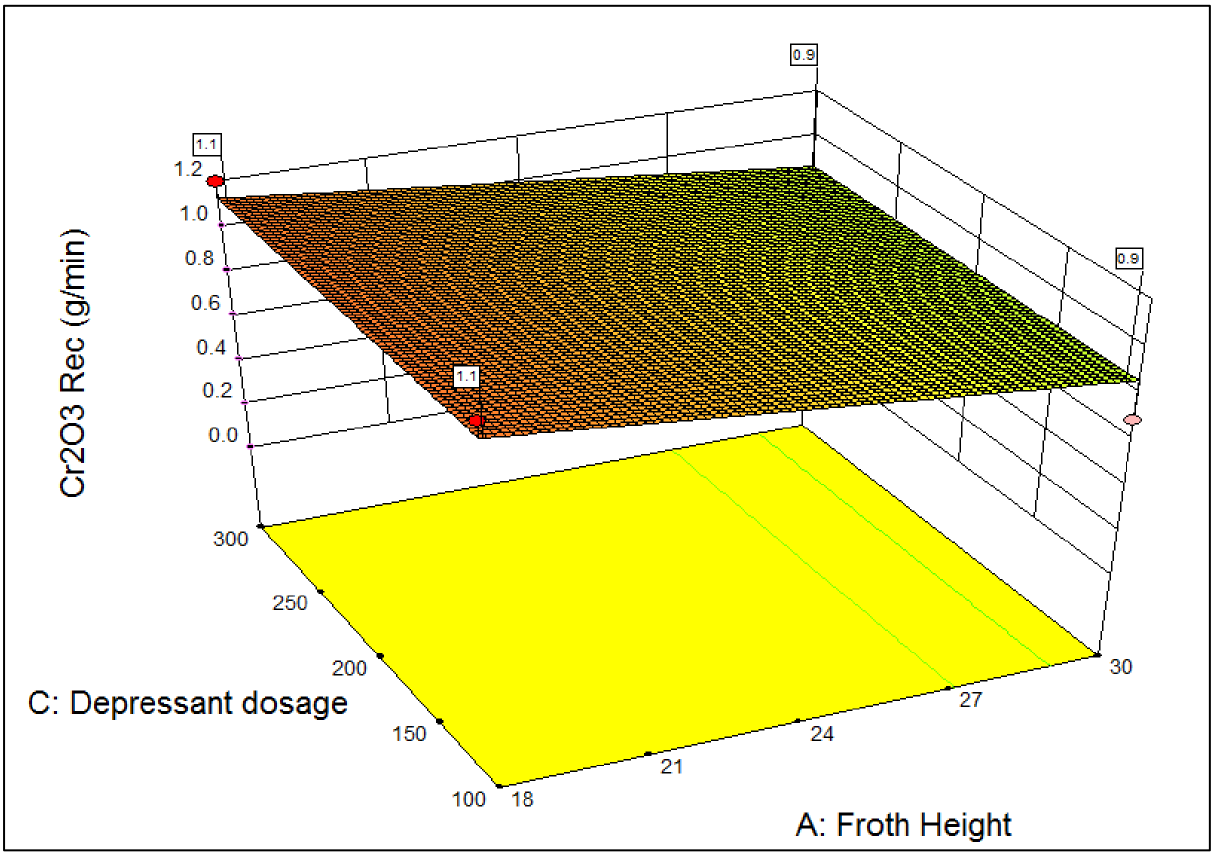


Figure D8 Effect of froth height and depressant dosage on chrome recovery keeping other factors at high levels (1.5cm/sec superficial air velocity and 30ppm frother)

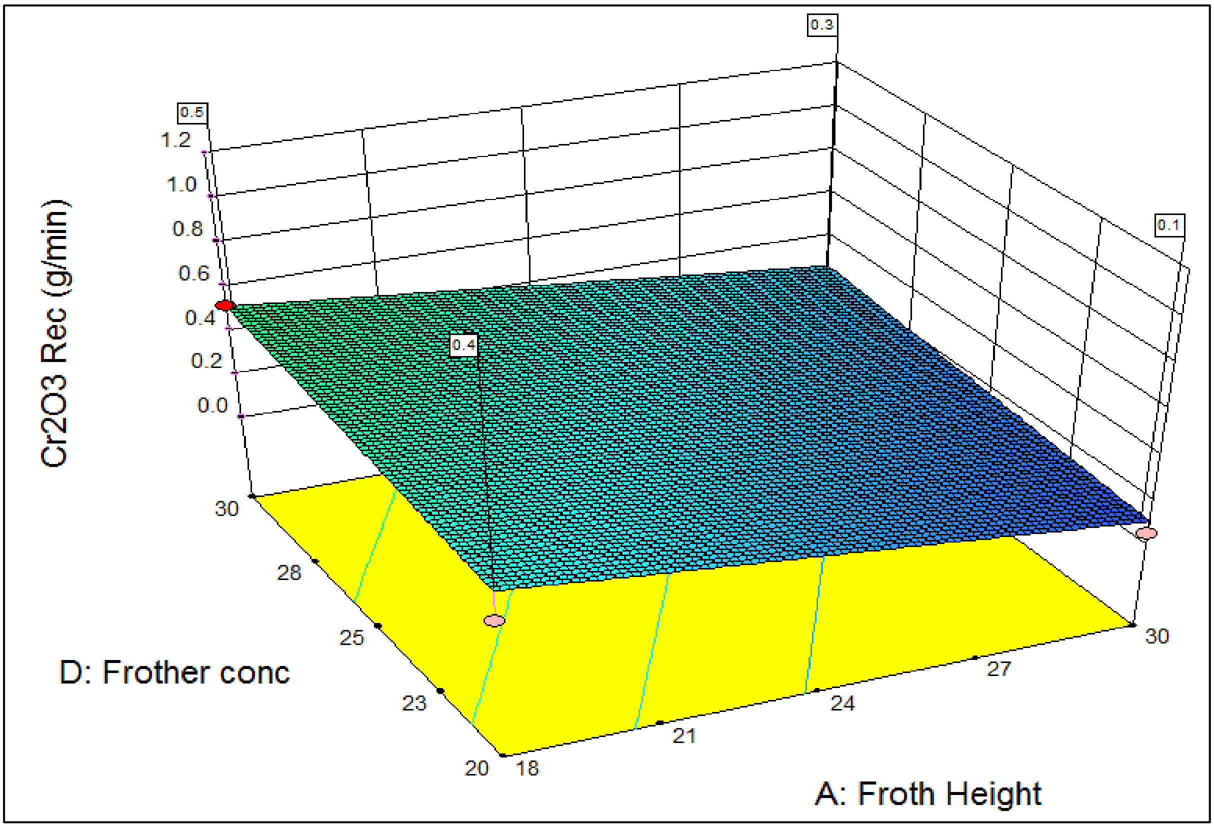


Figure D9 Effect of froth height and frother concentration on chrome recovery keeping other factors at low levels (0.5cm/sec superficial air velocity and 100g/t depressant)

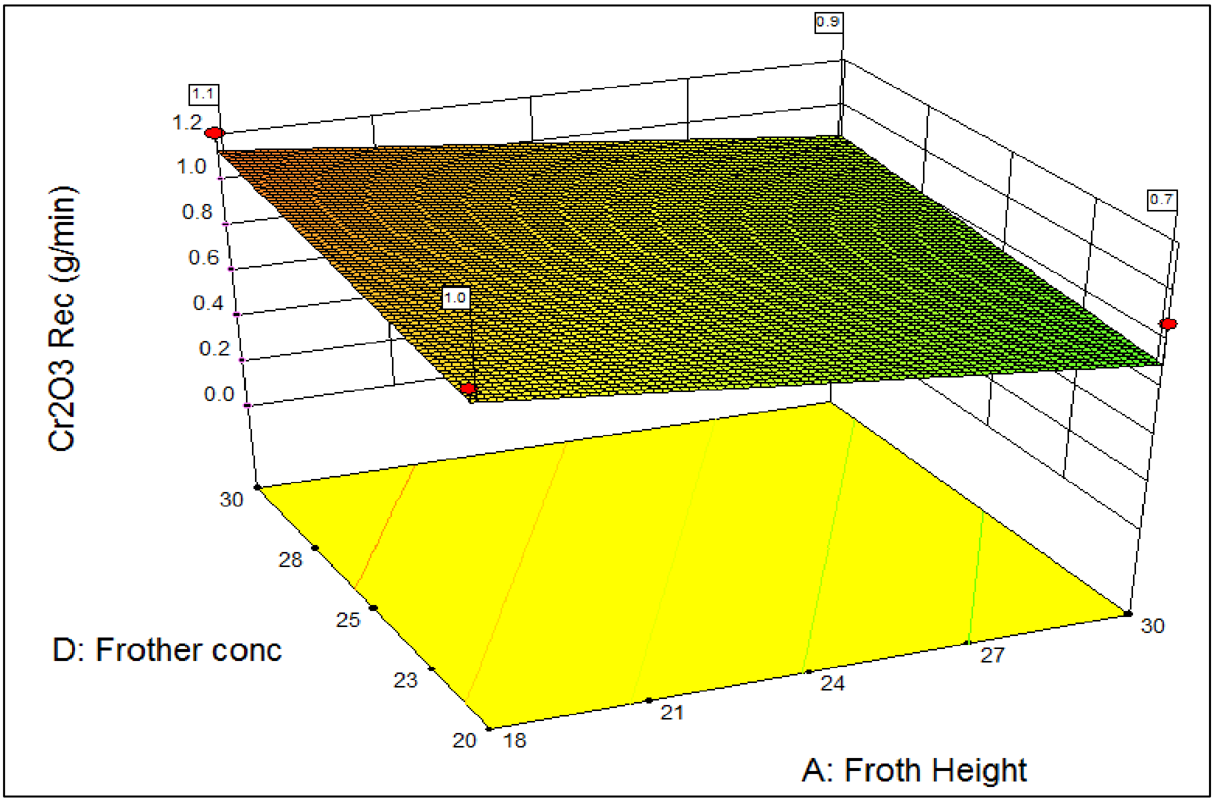


Figure D10 Effect of froth height and frother concentration on chrome recovery keeping other factors at high levels (1.5cm/sec superficial air velocity and 300g/t depressant)

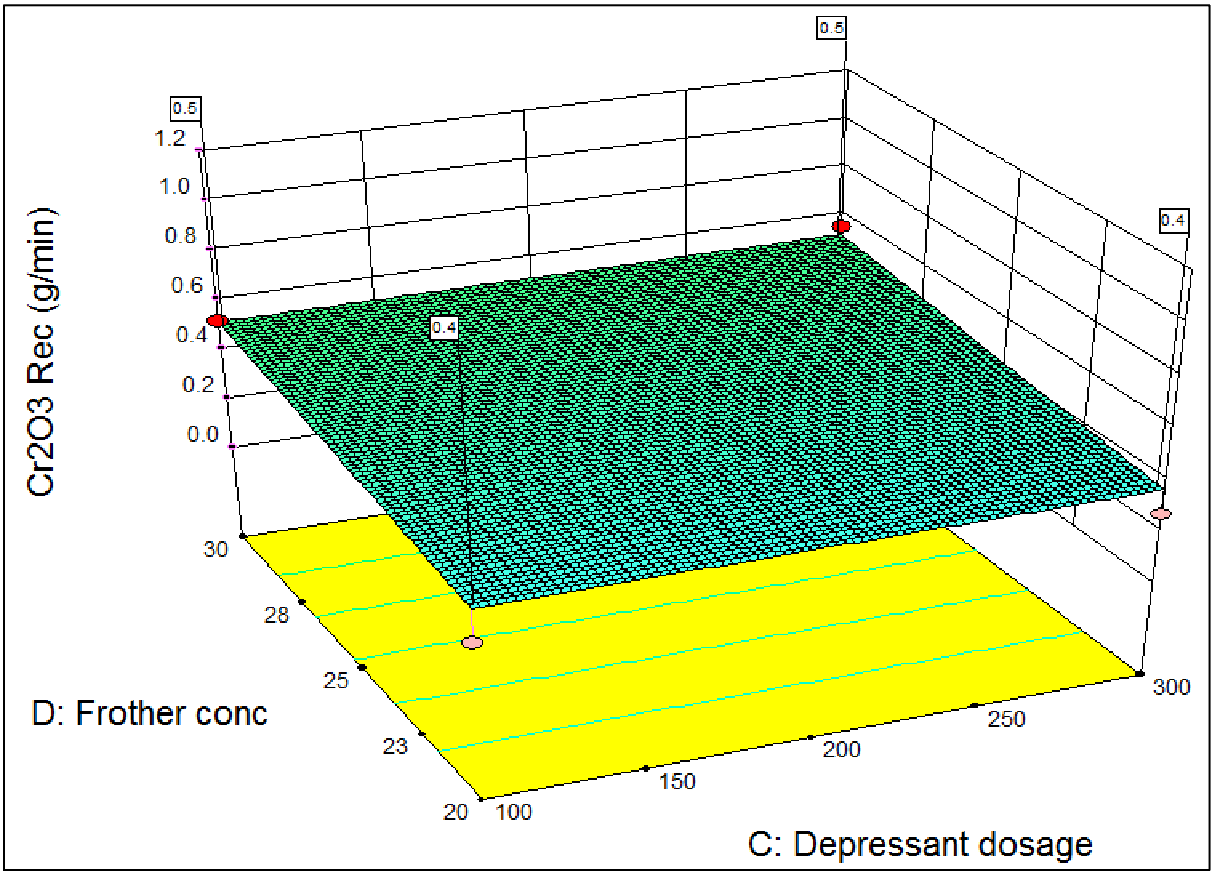


Figure D11 Effect of depressant dosage and frother concentration on chrome recovery keeping other factors at low levels (0.5cm/sec superficial air velocity and 18cm froth height)

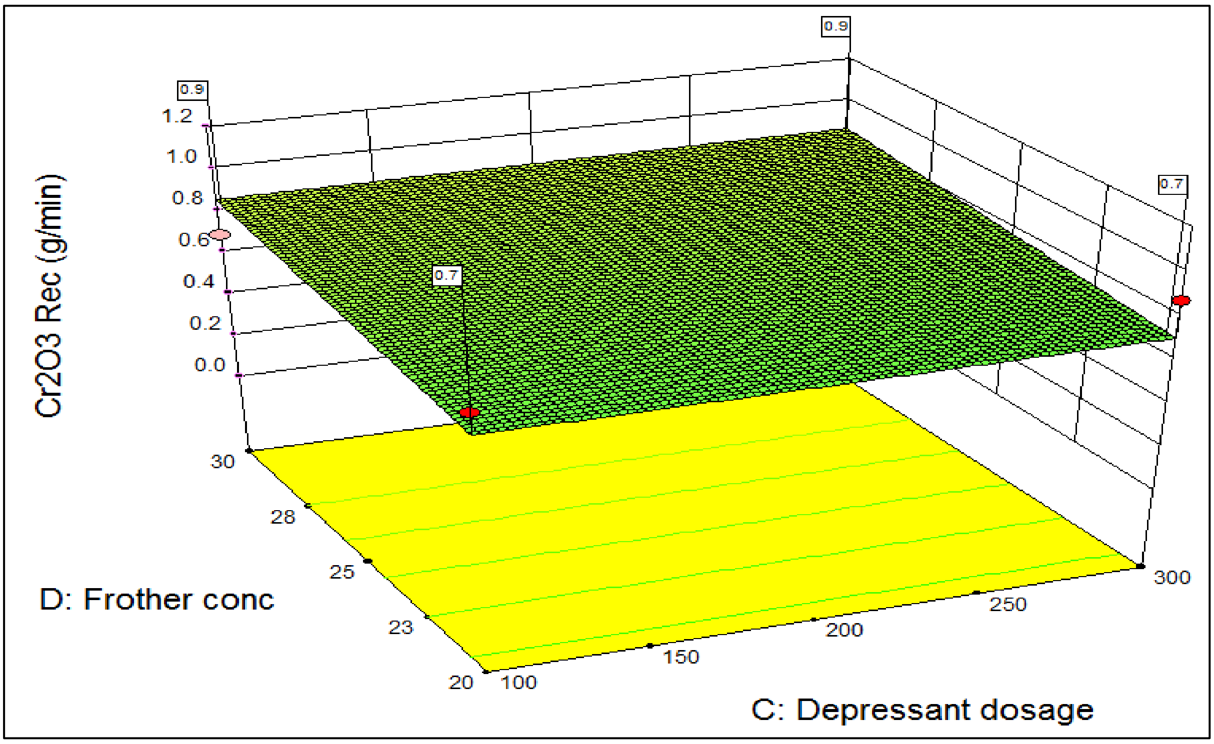


Figure D12 Effect of depressant dosage and frother concentration on chrome recovery keeping other factors at high levels (1.5cm/sec superficial air velocity and 30cm froth height)

Appendix-E

Response of Chrome Grade

Table E1 ANOVA model for chrome grade

Source model	Sum of Squares	df	Mean Square	F value	P value Prob>F	Significance
Model	146.98	8	18.37	36.10	0.0001	Significant
Froth Height-A	11.64	1	11.64	22.87	0.0020	
Superficial air velocity-B	27.07	1	27.07	53.20	0.0002	
Depressant dosage-C	61.45	1	61.45	120.74	0.0001	
Frother conc-D	9.19	1	9.19	18.06	0.0038	
AC	3.30	1	3.30	6.49	0.0383	
BC	22.78	1	22.78	44.77	0.0003	
BD	4.29	1	4.29	8.42	0.0229	
ABD	7.25	1	7.25	14.25	0.0069	
Residual	3.56	7	0.51			
Cor Total	150.54	15				

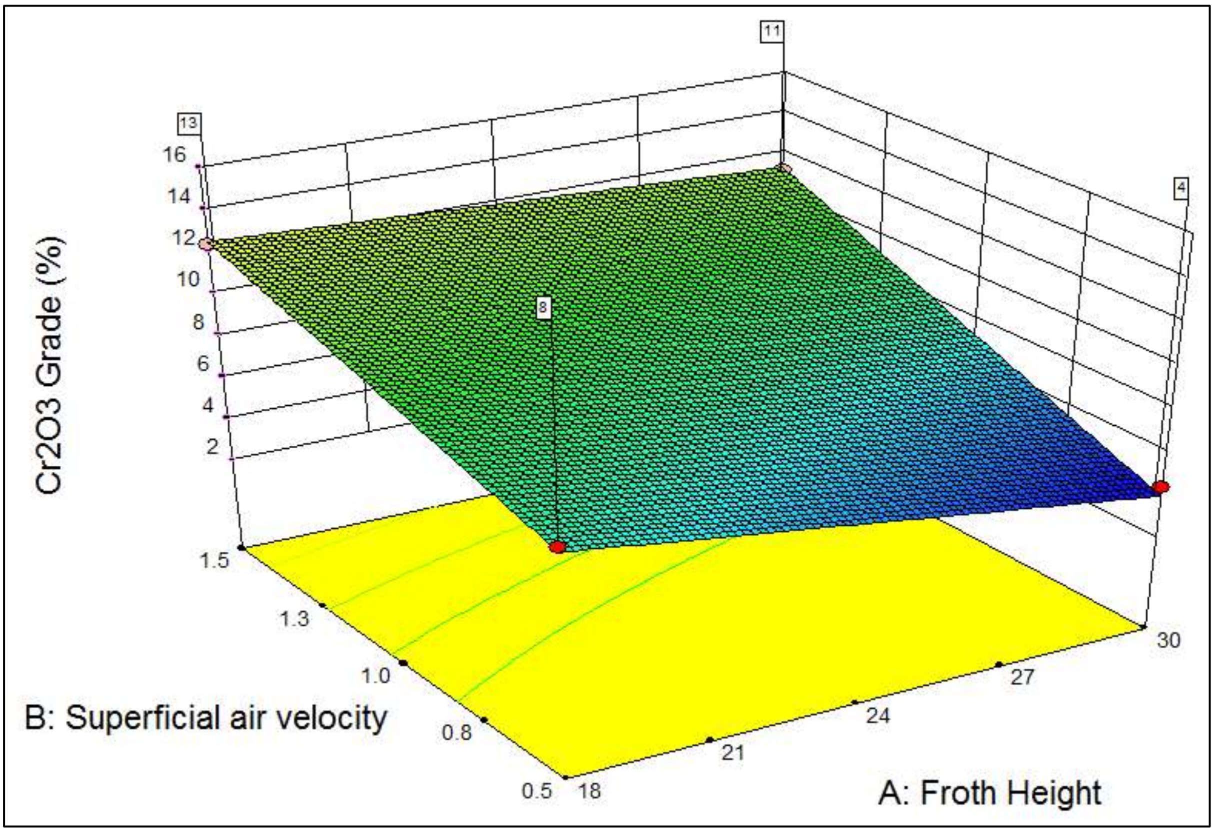


Figure E1 Effect of superficial air velocity and froth height on chrome grade keeping other factors at low levels (100g/t depressant and 20ppm frother)

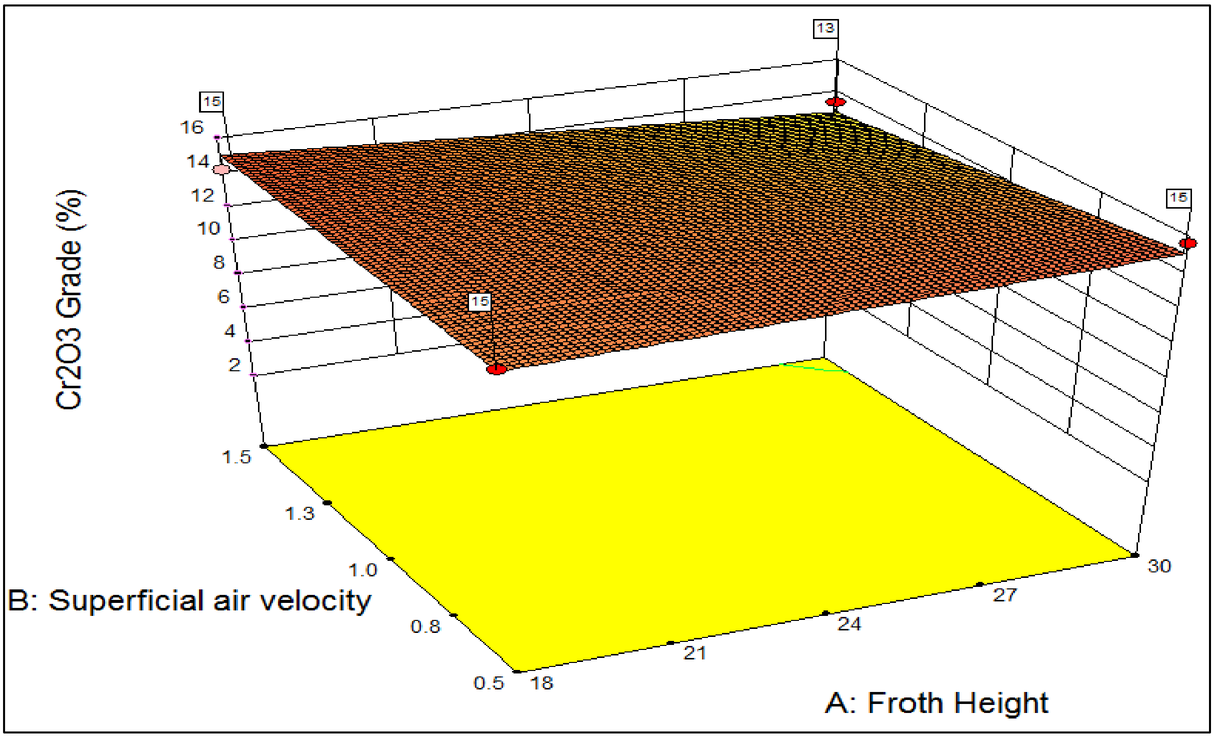


Figure E2 Effect of superficial air velocity and froth height on chrome grade keeping other factors at high levels (300g/t depressant and 30ppm frother)

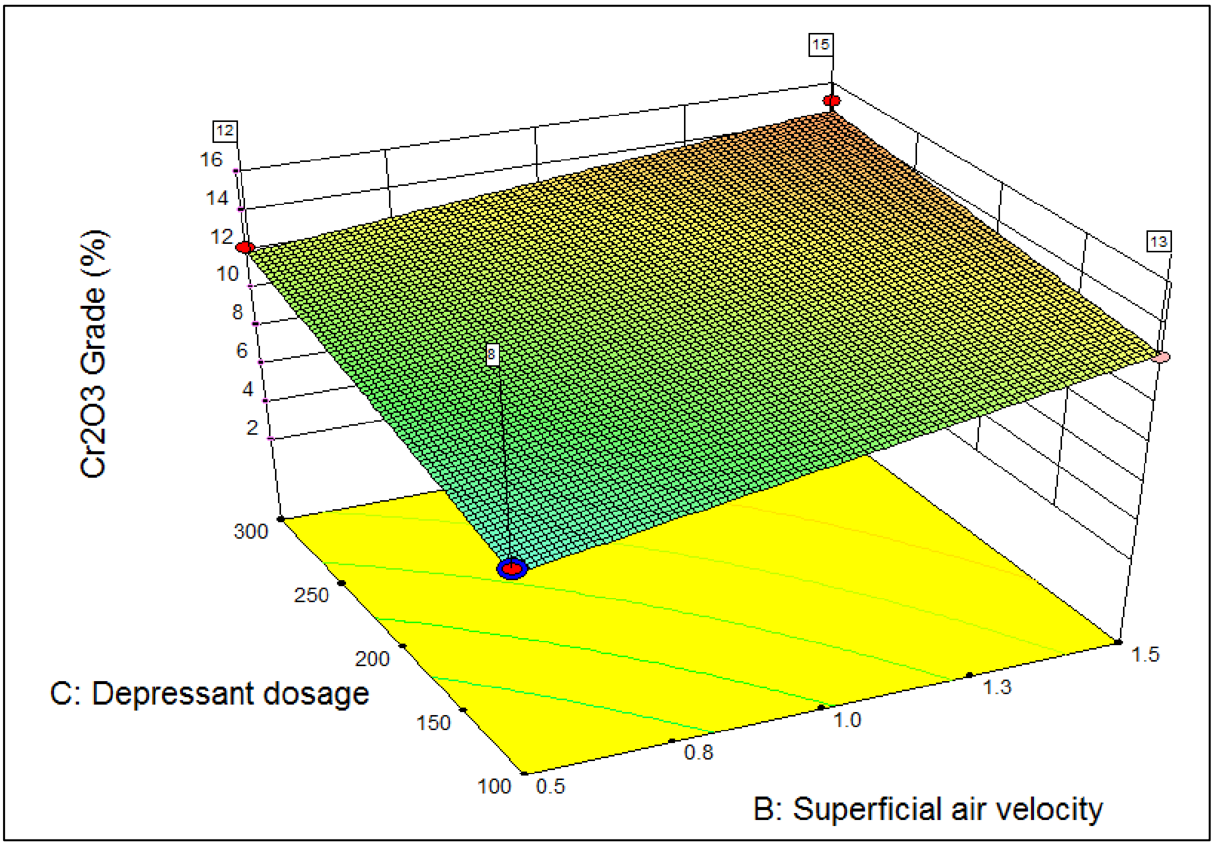


Figure E3 Effect of superficial air velocity and depressant dosage on chrome grade keeping other factors at low levels (18cm froth height and 20ppm frother)

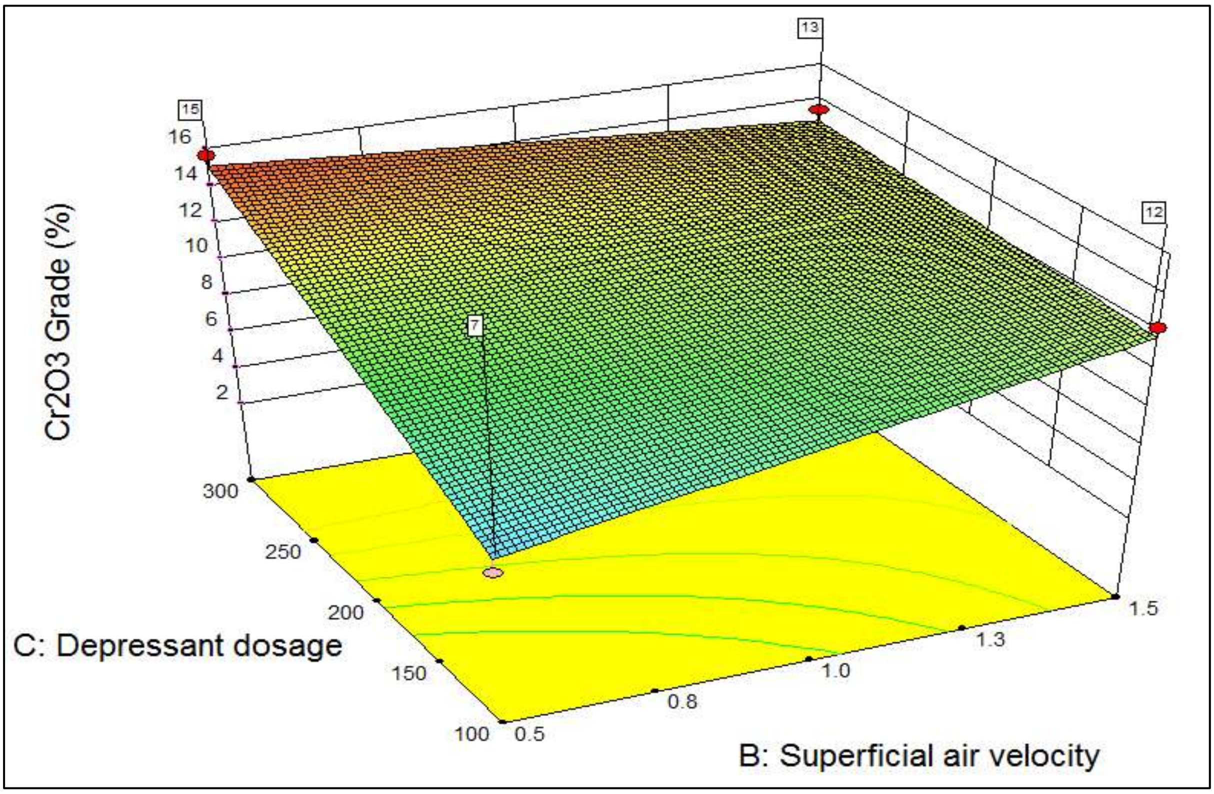


Figure E4 Effect of superficial air velocity and depressant dosage on chrome grade keeping other factors at high levels (30cm froth height and 30ppm frother)

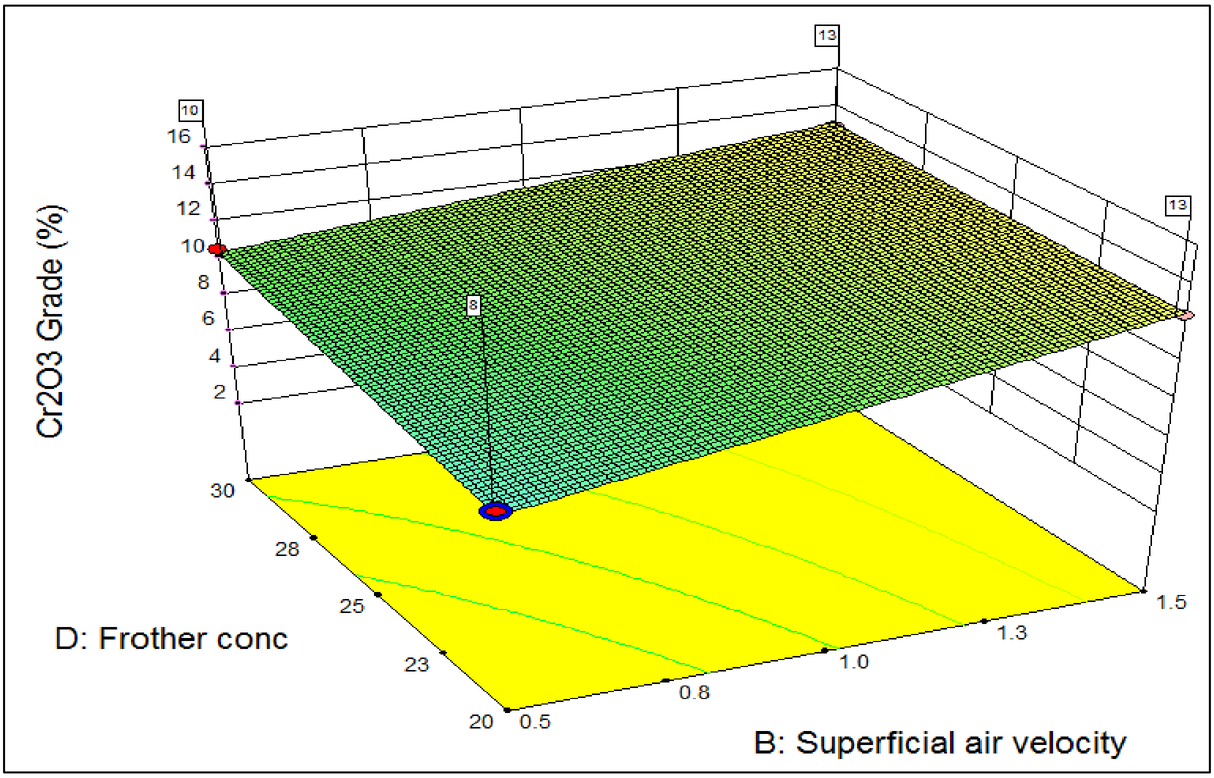


Figure E5 Effect of superficial air velocity and frother concentration on chrome grade keeping other factors at low levels (18cm froth height and 100g/t depressant)

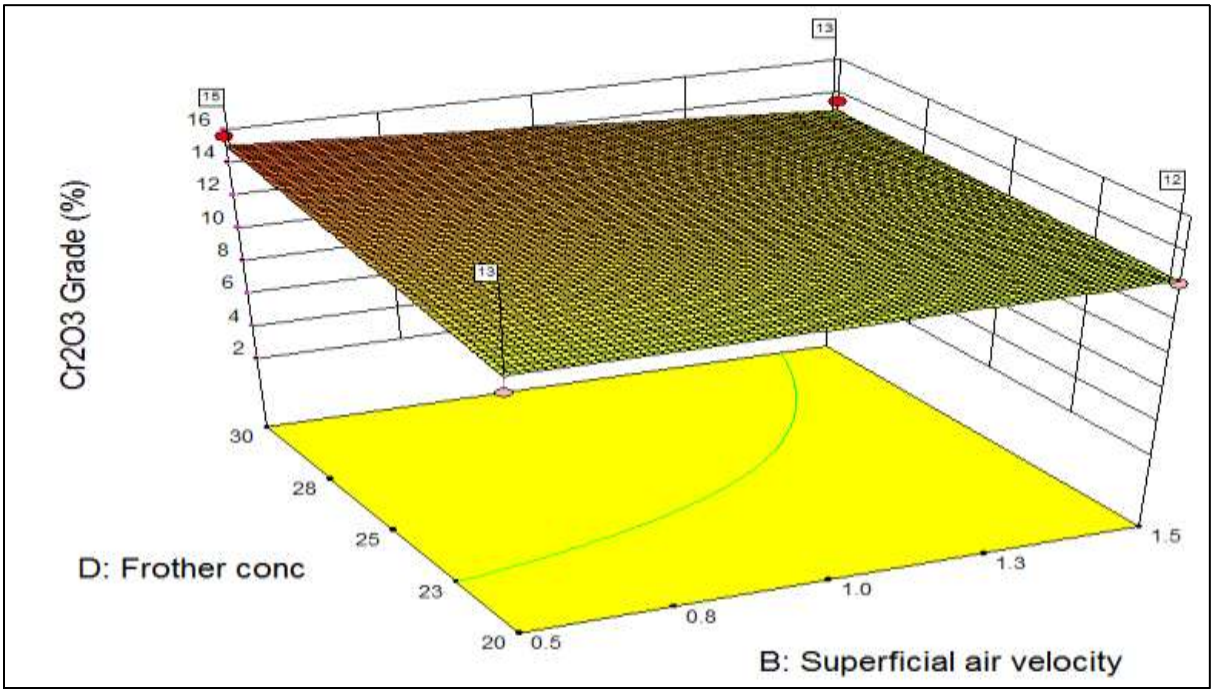


Figure E6 Effect of superficial air velocity and frother concentration on chrome grade keeping other factors at high levels (30cm froth height and 300g/t depressant)

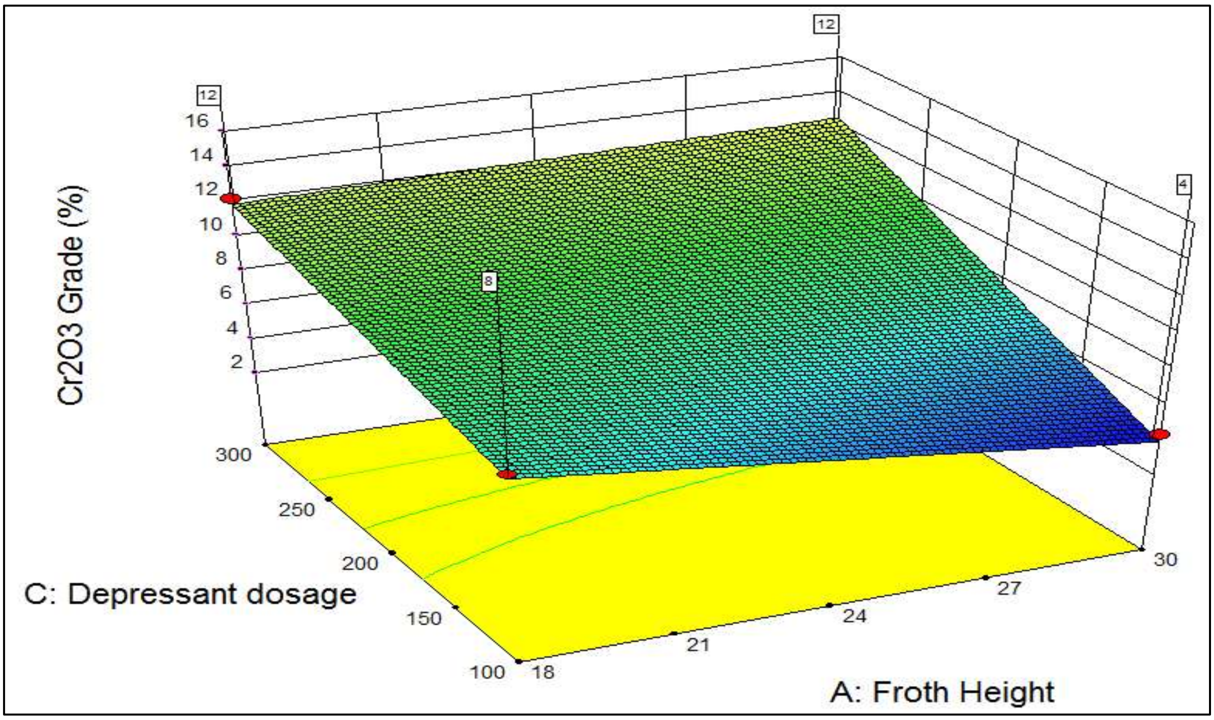


Figure E7 Effect of froth height and depressant dosage on chrome grade keeping other factors at low levels (0.5cm/sec superficial air velocity and 20ppm frother)

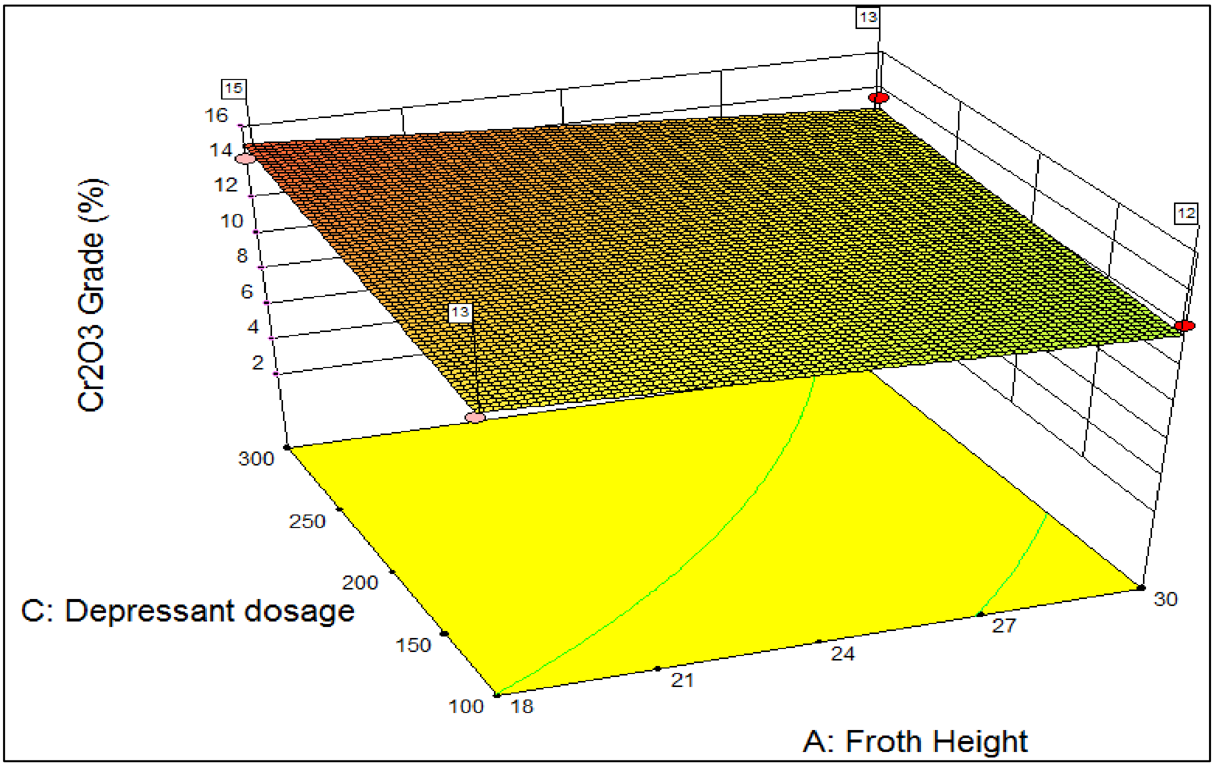


Figure E8 Effect of froth height and depressant dosage on chrome grade keeping other factors at high levels (1.5cm/sec superficial air velocity and 30ppm frother)

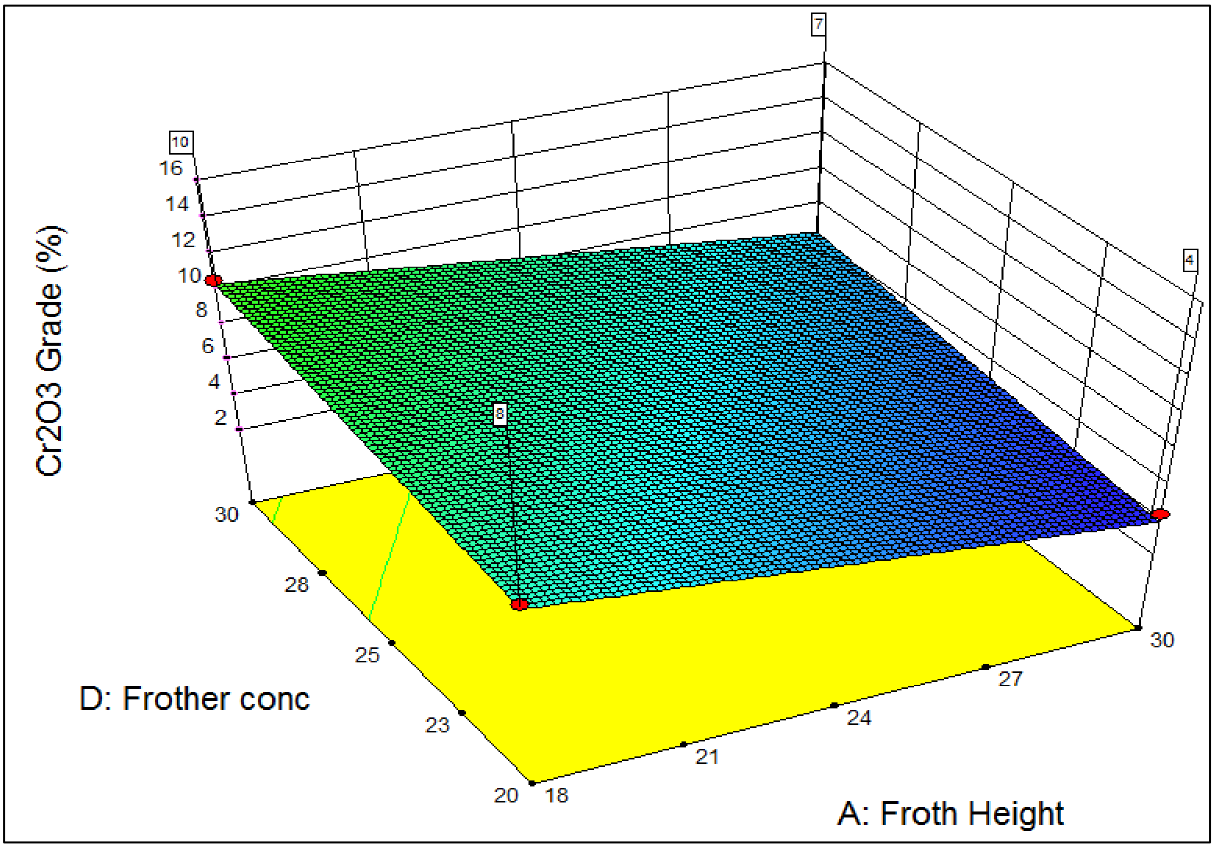


Figure E9 Effect of froth height and frother concentration on chrome grade keeping other factors at low levels (0.5cm/sec superficial air velocity and 100g/t depressant)

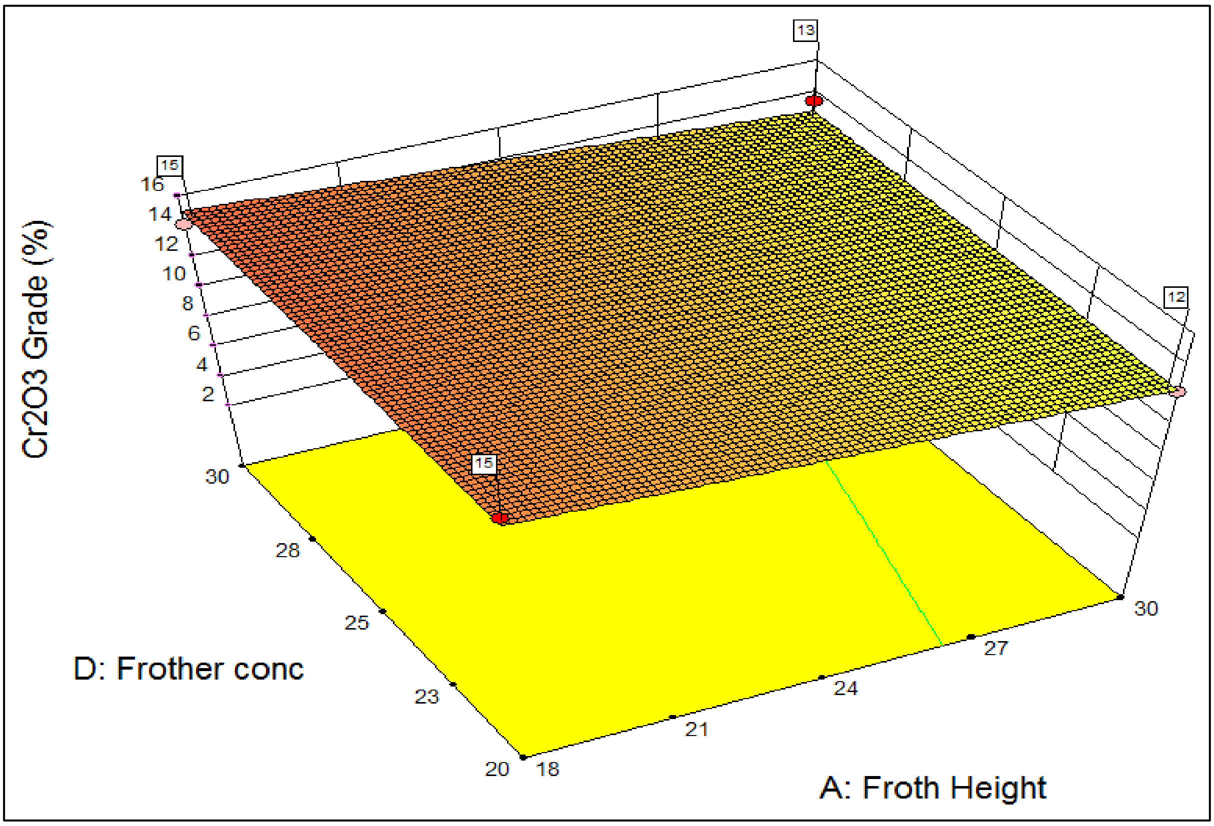


Figure E10 Effect of froth height and frother concentration on chrome grade keeping other factors at high levels (1.5cm/sec superficial air velocity and 300g/t depressant)

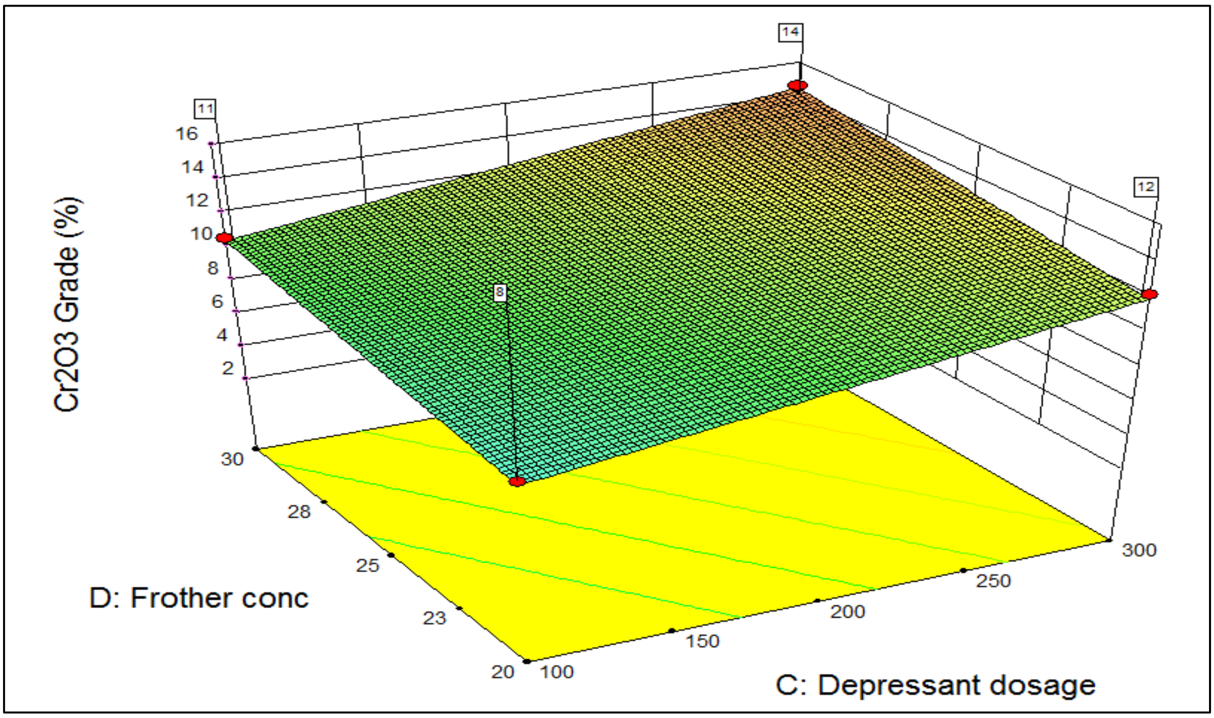


Figure E11 Effect of depressant dosage and frother concentration on chrome grade keeping other factors at low levels (0.5cm/sec superficial air velocity and 18cm froth height)

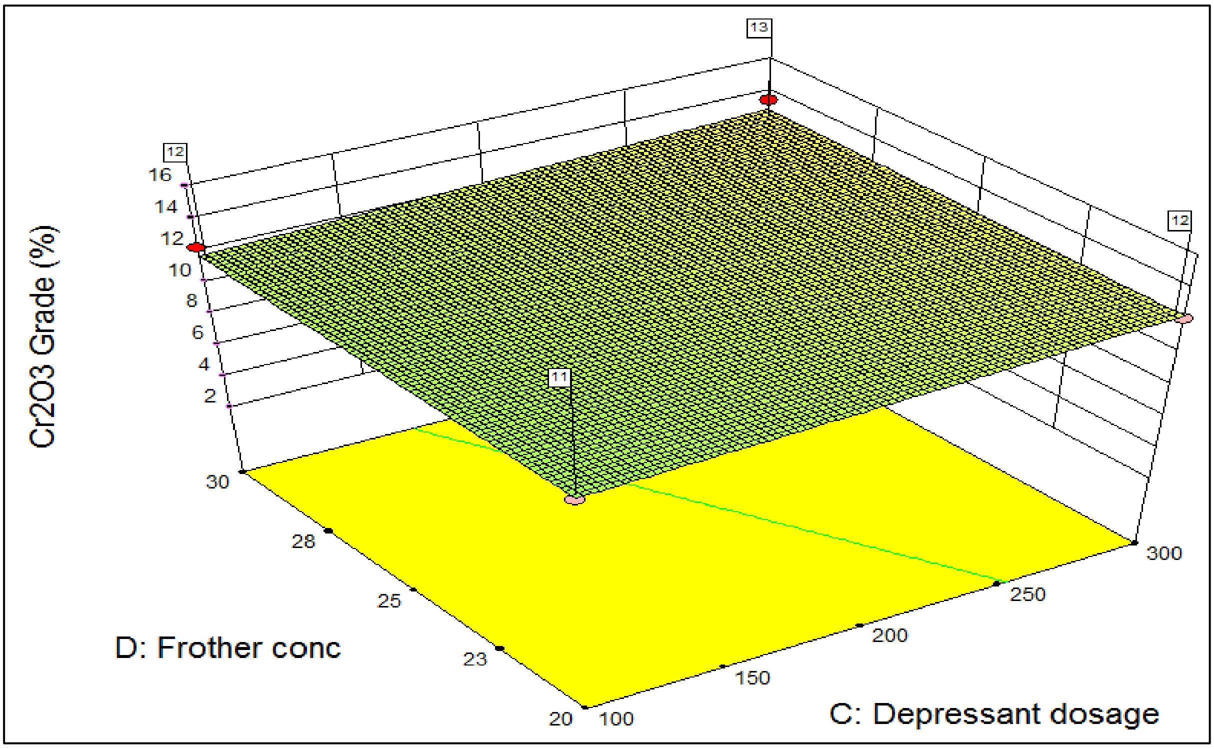


Figure E12 Effect of depressant dosage and frother concentration on chrome grade keeping other factors at high levels (1.5cm/sec superficial air velocity and 30cm froth height)

Appendix-F

Response of PGM Recovery

Table F1 ANOVA model for PGM recovery

Source model	Sum of Squares	df	Mean Square	F value	P value Prob>F	Significance
Model	39.87	4	9.97	24.11	0.0001	Significant
Froth height -A	11.95	1	11.95	28.90	0.0002	
Superficial air velocity-B	21.52	1	21.52	52.06	<0.0001	
BC	4.91	1	4.91	11.88	0.0055	
ACD	1.49	1	1.49	3.61	0.0840	
Residual	4.55	11	0.41			
Cor Total	44.41	15				

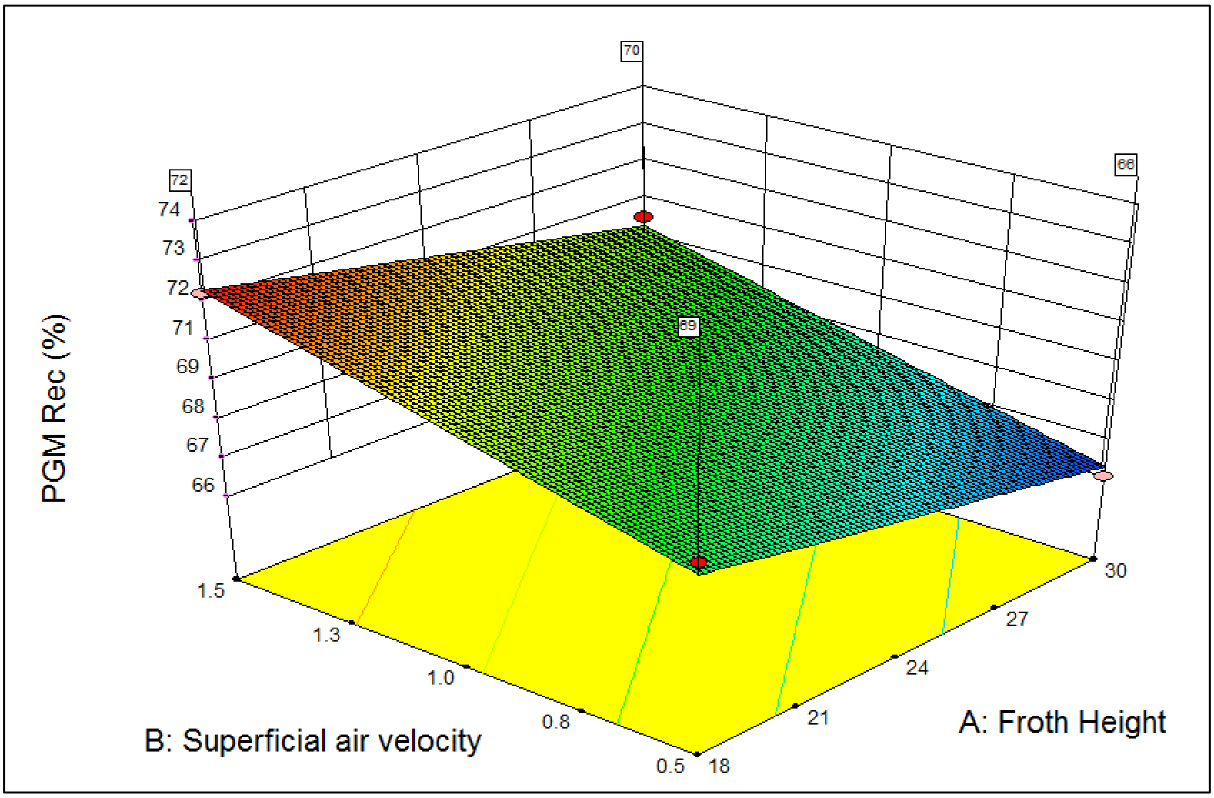


Figure F1 Effect of superficial air velocity and froth height on PGM recovery keeping other factors at low levels (100g/t depressant and 20ppm frother)

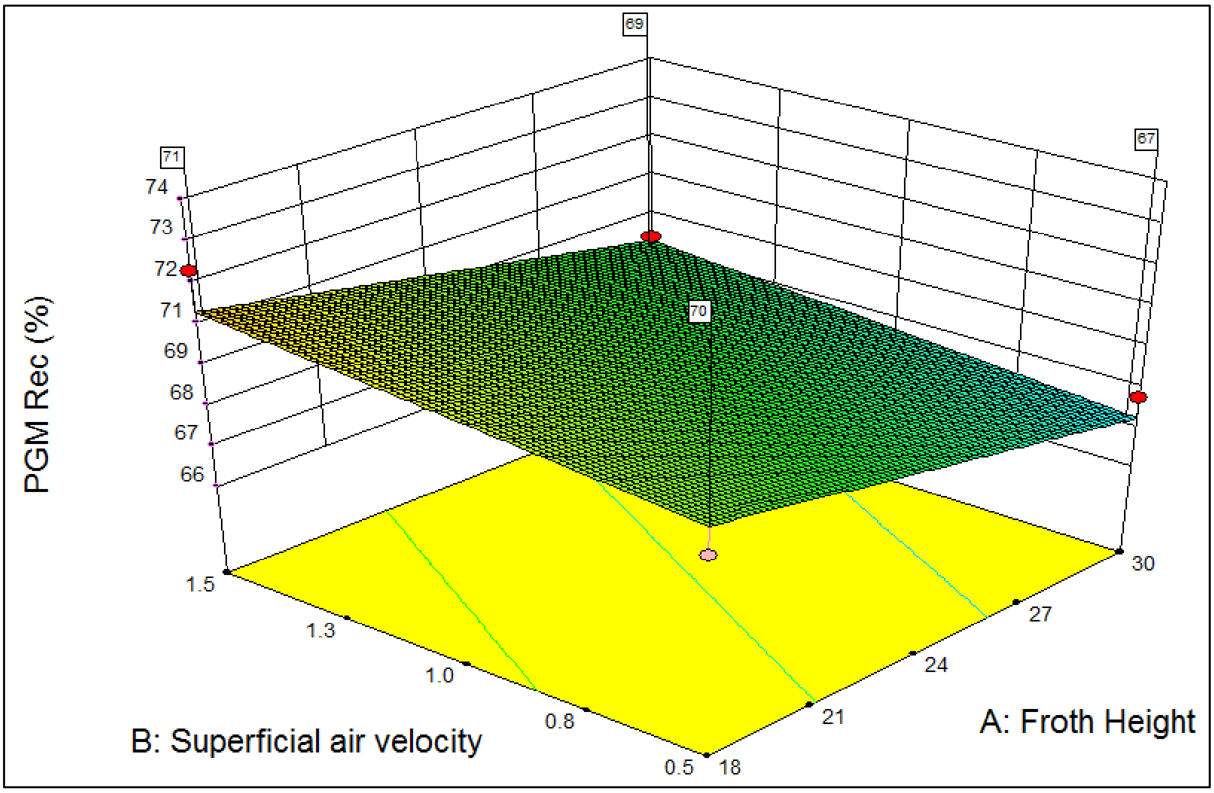


Figure F2 Effect of superficial air velocity and froth height on PGM recovery keeping other factors at high levels (300g/t depressant and 30ppm frother)

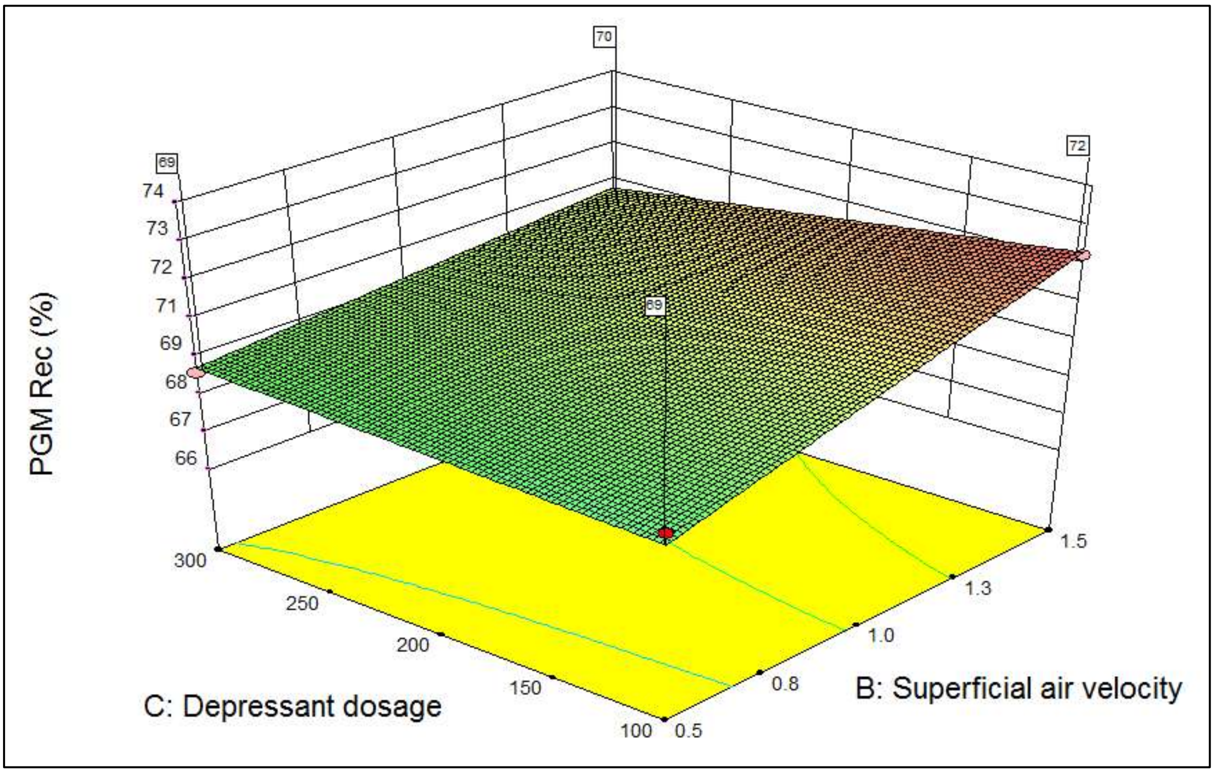


Figure F3 Effect of superficial air velocity and depressant dosage on PGM recovery keeping other factors at low levels (18cm froth height and 20ppm frother)

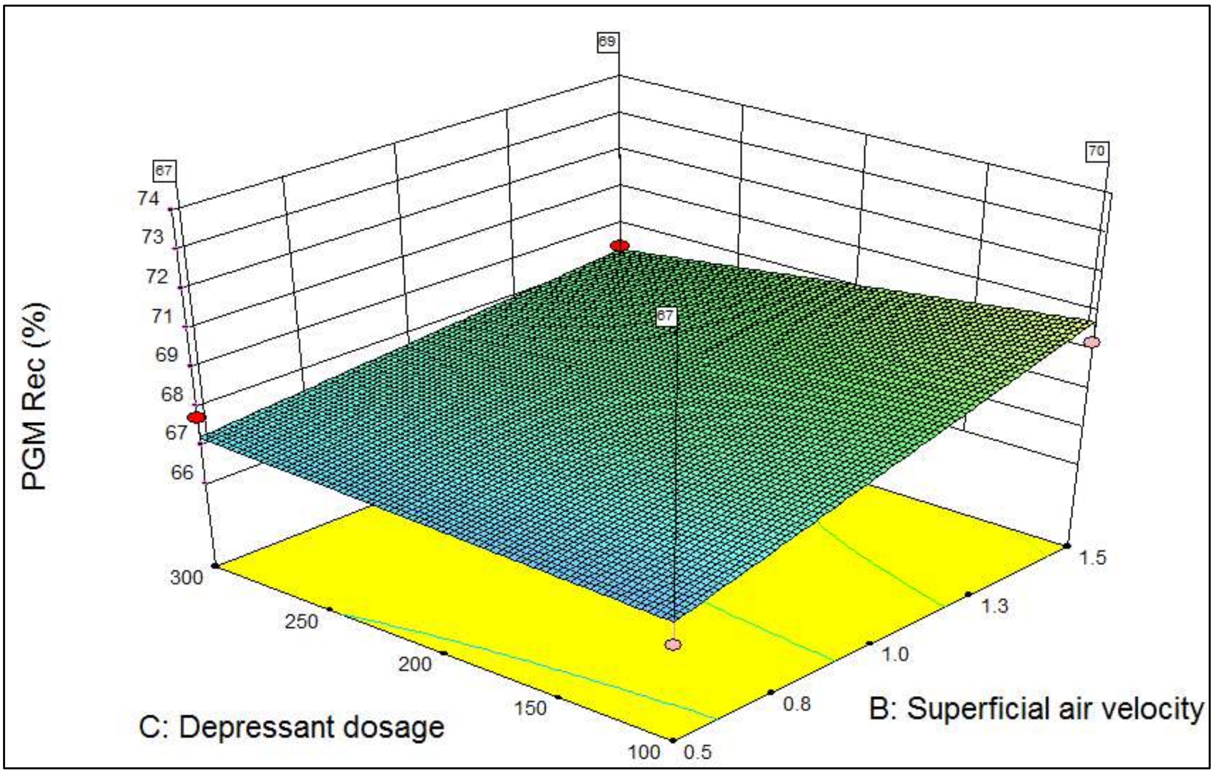


Figure F4 Effect of superficial air velocity and depressant dosage on PGM recovery keeping other factors at high levels (30cm froth height and 30ppm frother)

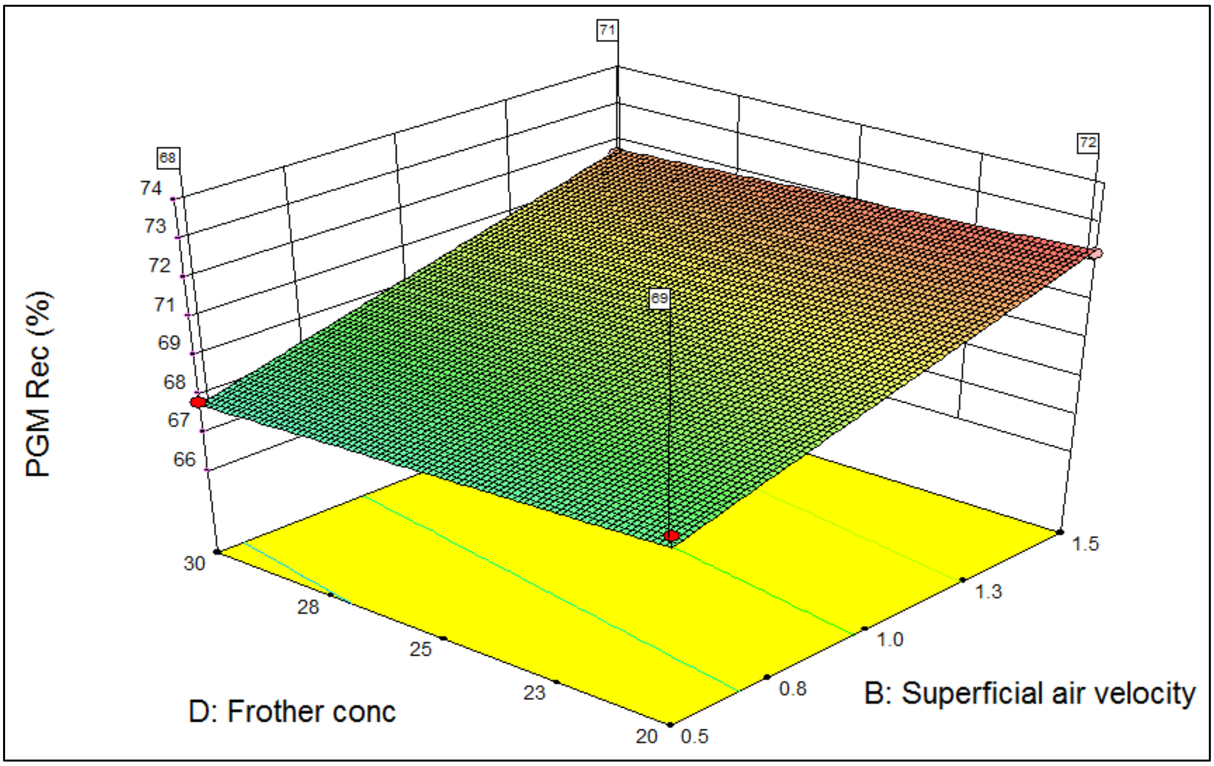


Figure F5 Effect of superficial air velocity and frother concentration on PGM recovery keeping other factors at low levels (18cm froth height and 100g/t depressant)

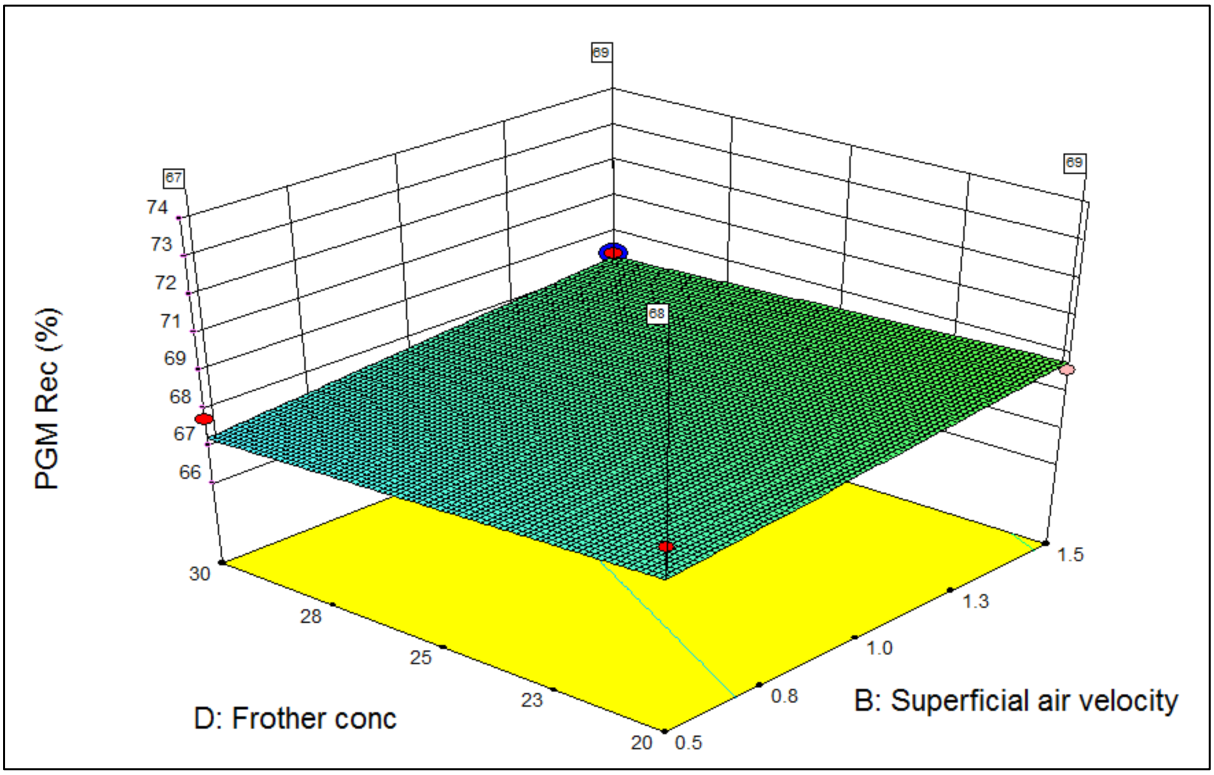


Figure F6 Effect of superficial air velocity and frother concentration on PGM recovery keeping other factors at high levels (30cm froth height and 300g/t depressant)

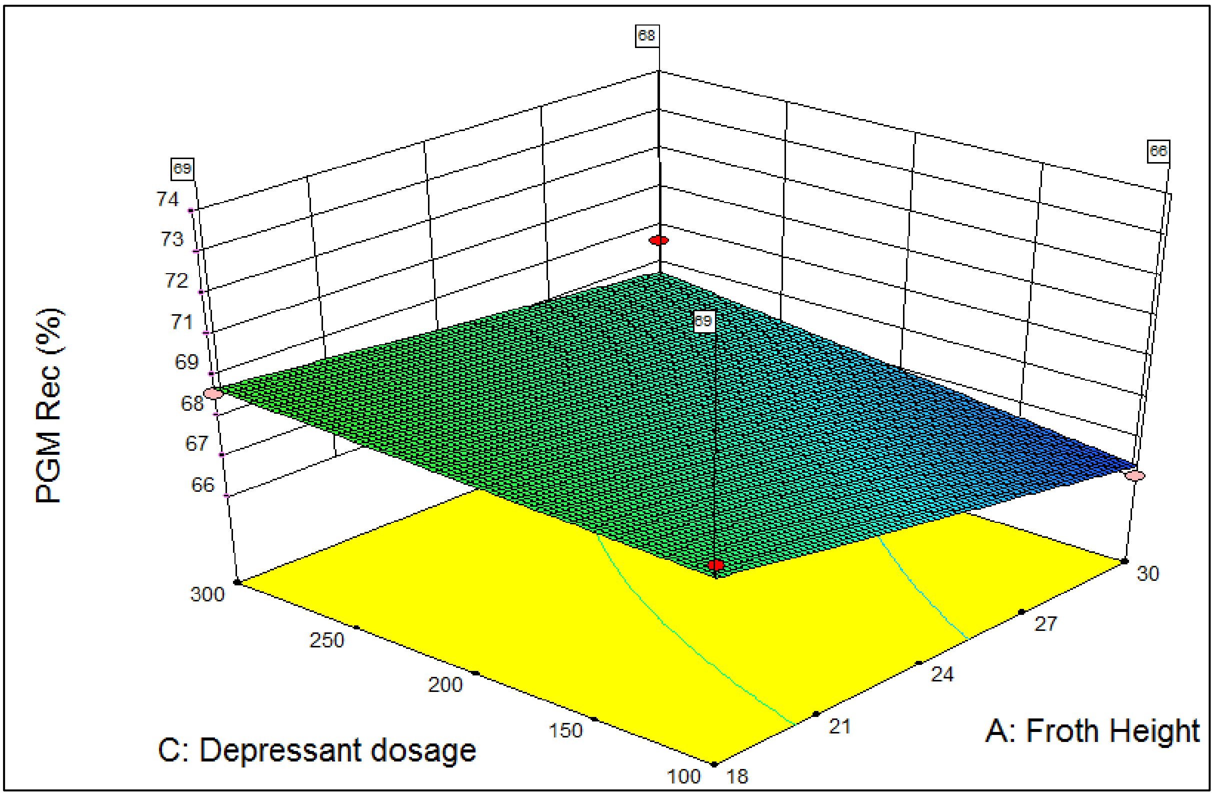


Figure F7 Effect of depressant dosage and froth height on PGM recovery keeping other factors at low levels (0.5cm/sec froth superficial air velocity and 20ppm frother)

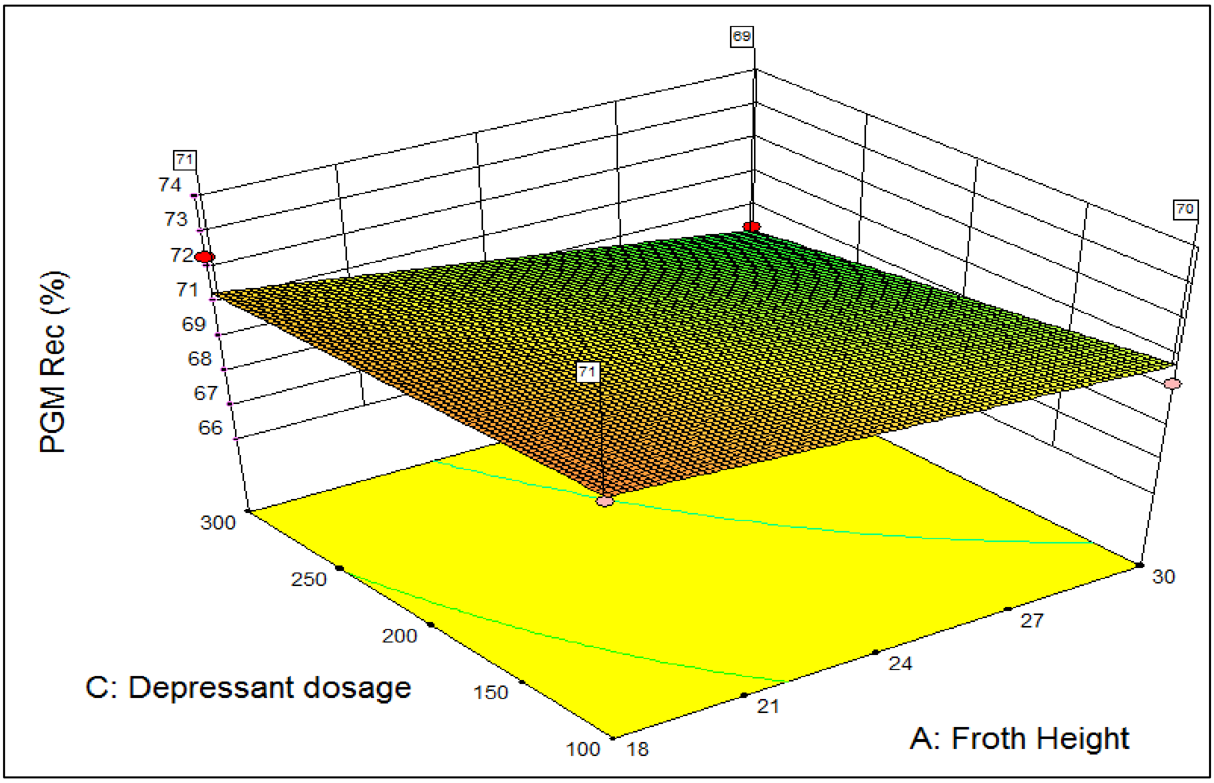


Figure F8 Effect of depressant dosage and froth height on PGM recovery keeping other factors at high levels (1.5cm/sec froth superficial air velocity and 30ppm frother)

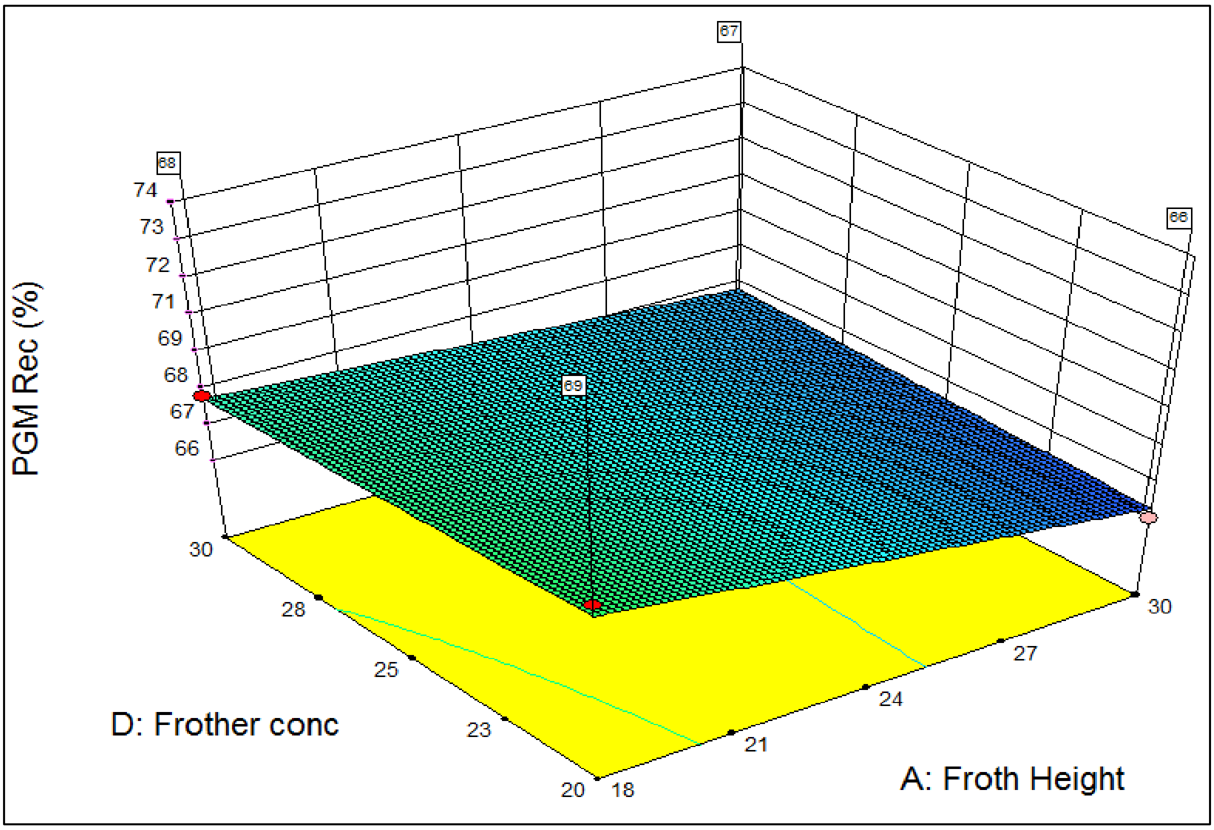


Figure F9 Effect of frother concentration and froth height on PGM recovery keeping other factors at low levels (0.5cm/sec froth superficial air velocity and 100g/t depressant)

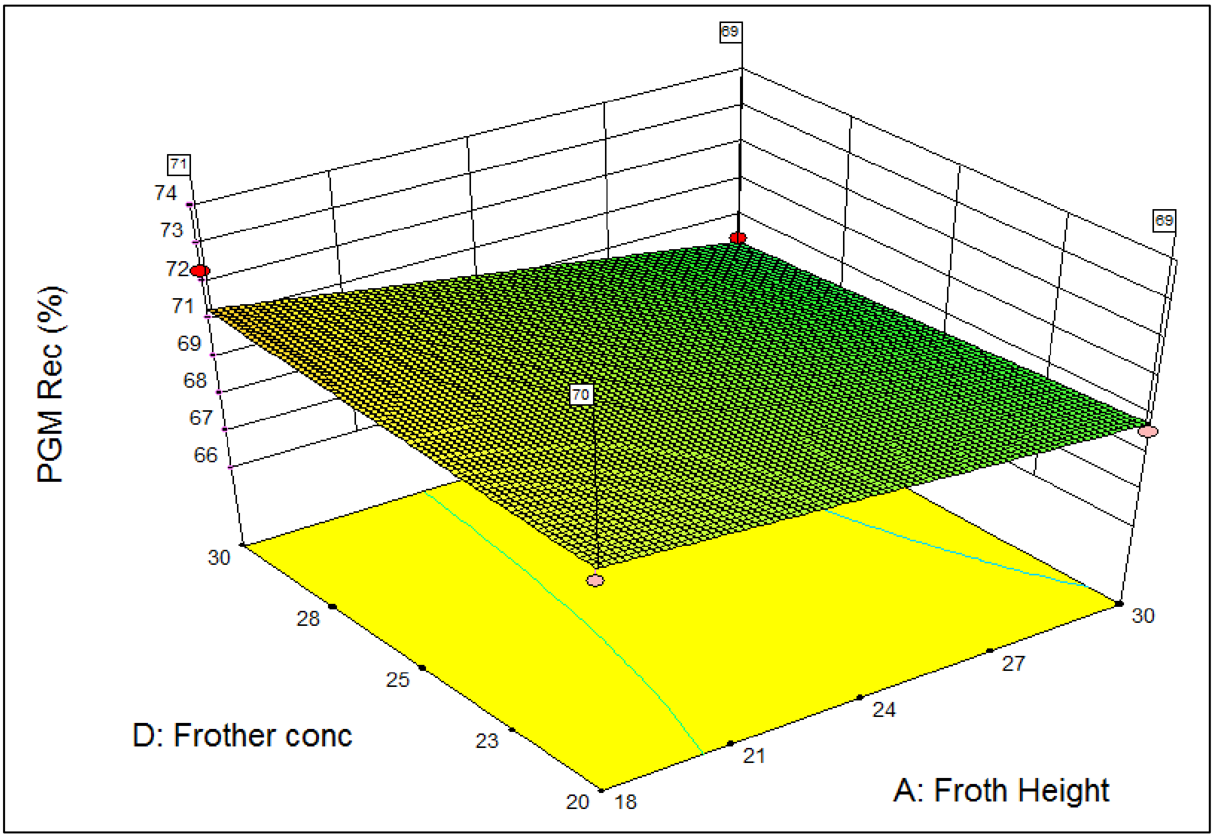


Figure F10 Effect of frother concentration and froth height on PGM recovery keeping other factors at high levels (1.5cm/sec froth superficial air velocity and 300g/t depressant)

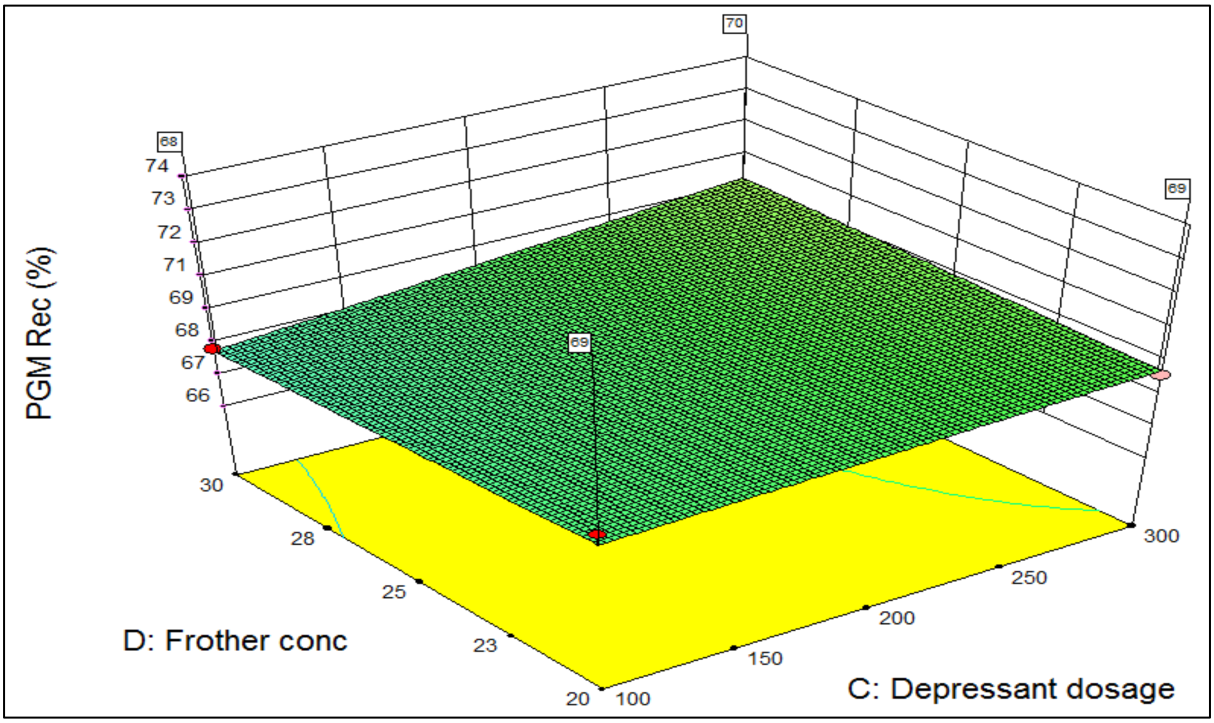


Figure F11 Effect of depressant dosage and frother concentration on PGM recovery keeping other factors at low levels (0.5cm/sec superficial air velocity and 18cm froth height)

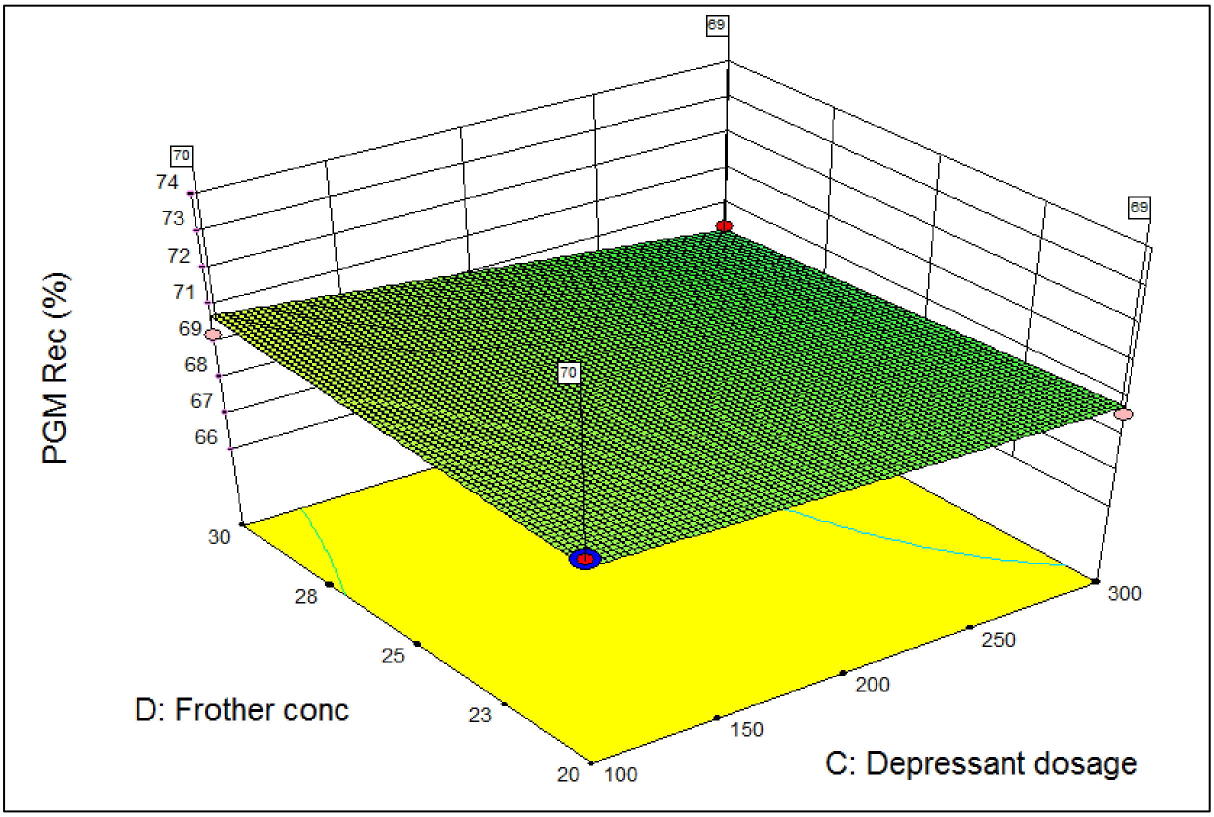


Figure F12 Effect of depressant dosage and frother concentration on PGM recovery keeping other factors at high levels (1.5cm/sec superficial air velocity and 30cm froth height)

Appendix-G

Response of PGM Grade

Table G1 ANOVA model for PGM grade

Source model	Sum of Squares	df	Mean Square	F value	P value Prob>F	Significance
Model	4.53	3	1.51	25.57	0.0001	Significant
Froth Height-A	1.32	1	1.32	22.36	0.0005	
Superficail Air Velocity-B	2.12	1	2.12	35.91	0.0001	
BD	1.09	1	1.09	18.44	0.0010	
Residual	0.71	12	0.059			
Cor Total	5.24	15				

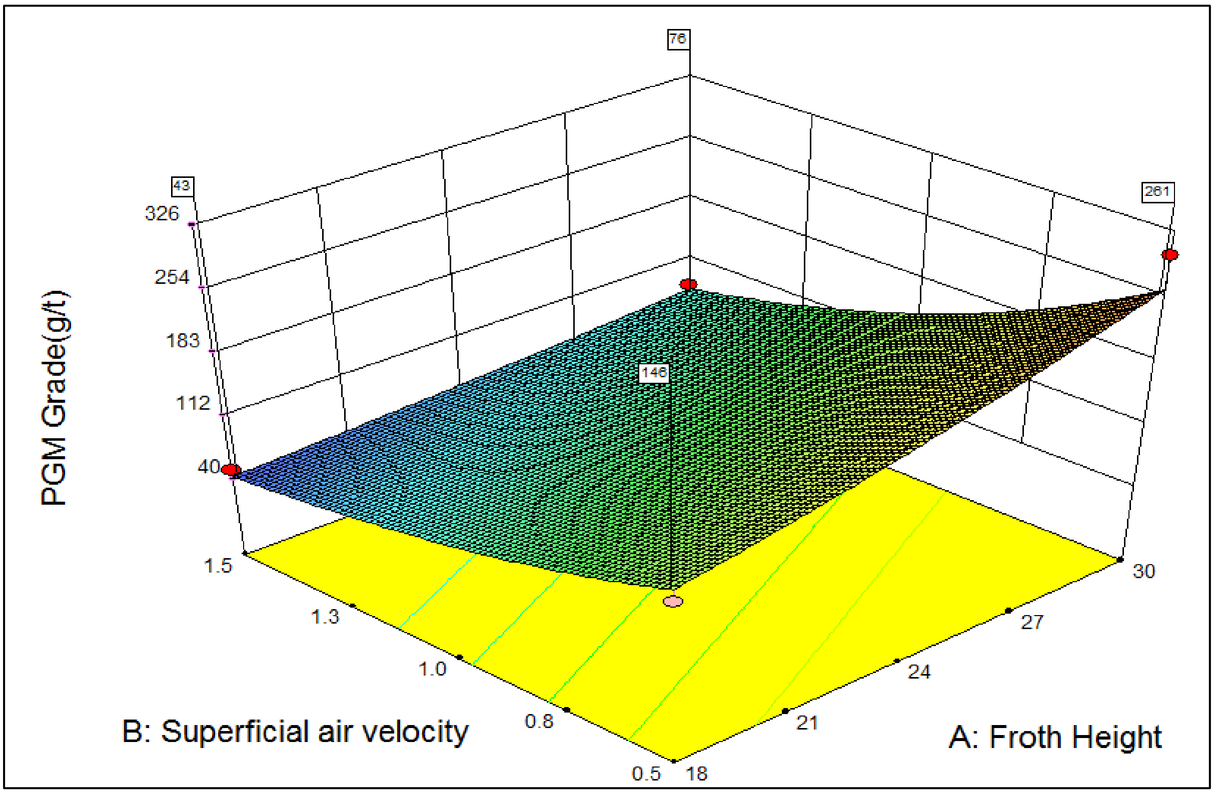


Figure F1 Effect of superficial air velocity and froth height on PGM grade keeping other factors at low levels (100g/t depressant and 20ppm frother)

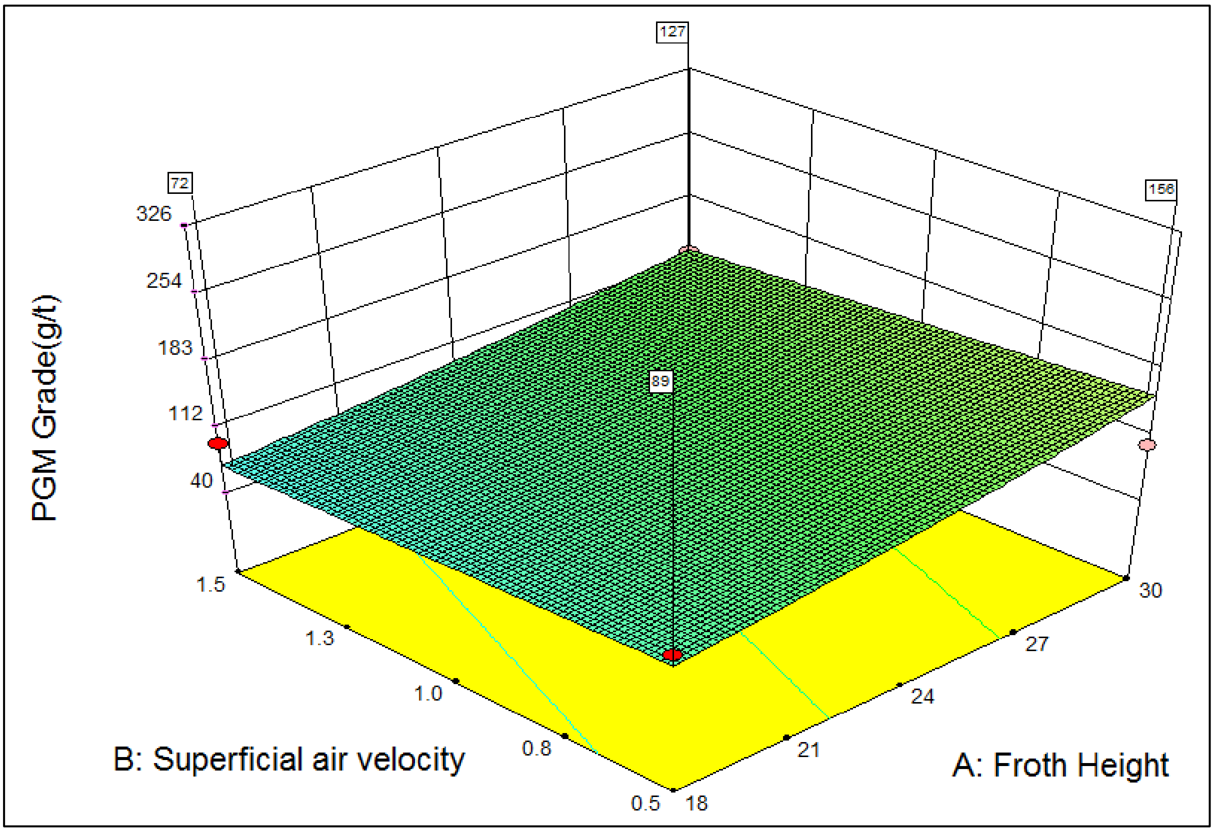


Figure G2 Effect of superficial air velocity and froth height on PGM grade keeping other factors at high levels (300g/t depressant and 30ppm frother)

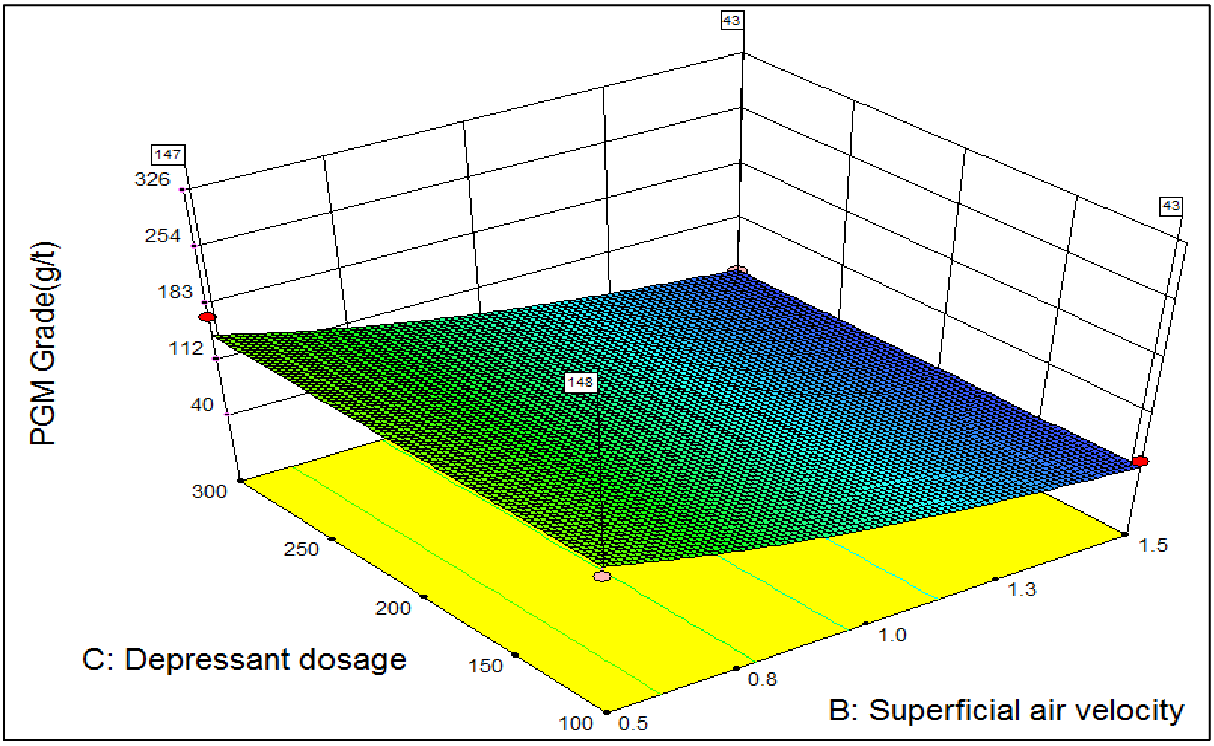


Figure G3 Effect of superficial air velocity and depressant dosage on PGM grade keeping other factors at low levels (100g/t depressant and 20ppm frother)

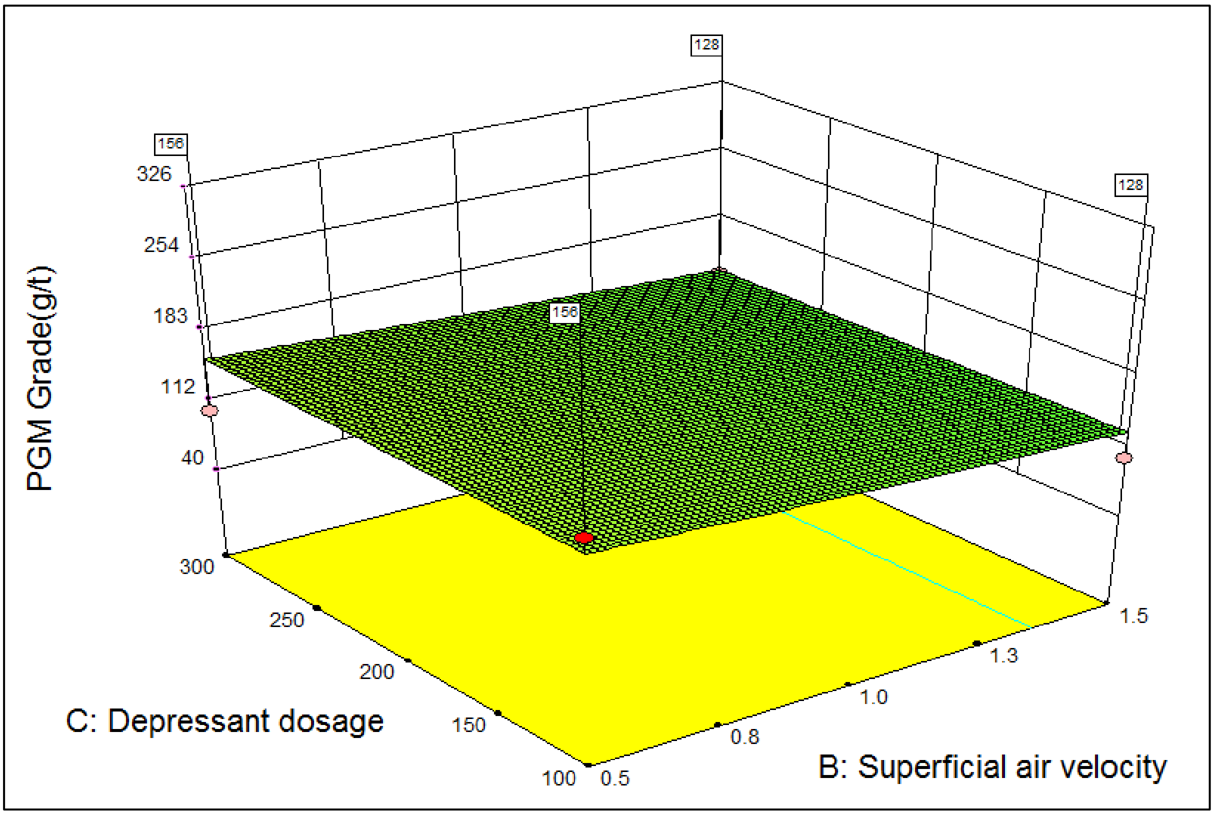


Figure G4 Effect of superficial air velocity and depressant dosage on PGM grade keeping other factors at high levels (300g/t depressant and 30ppm frother)

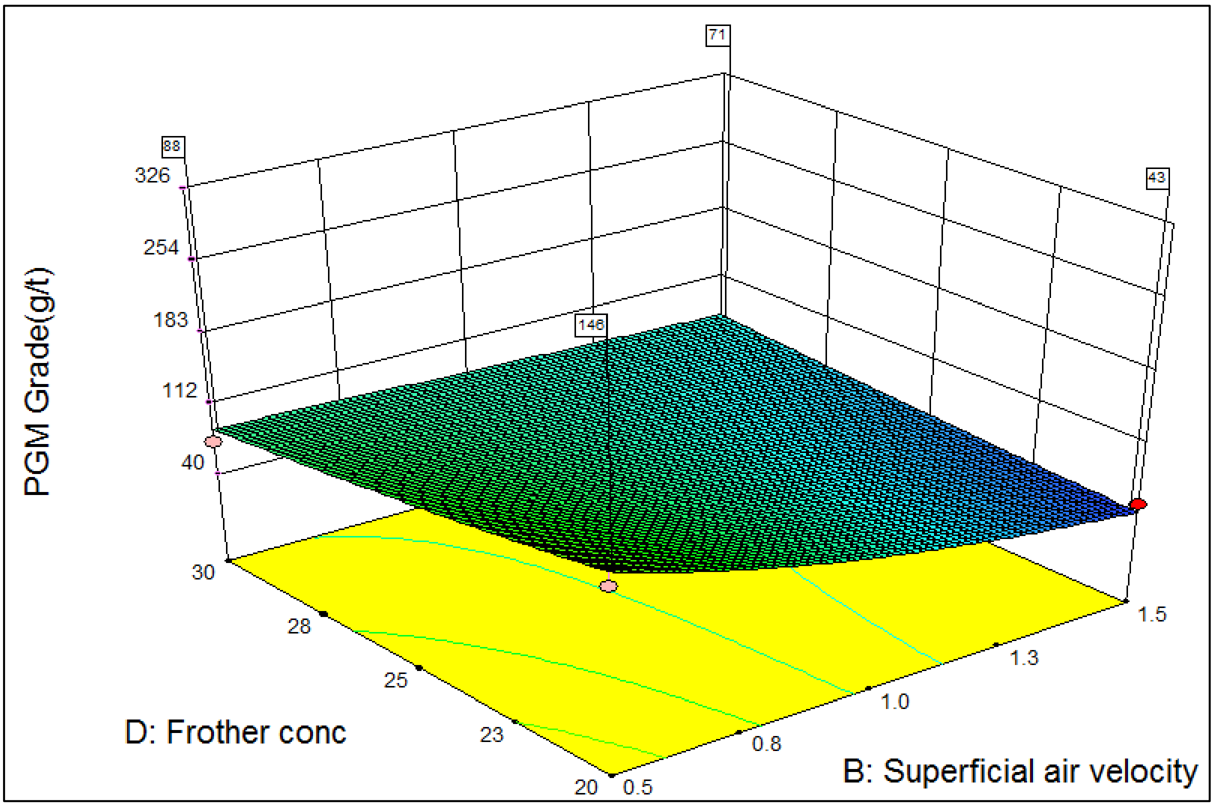


Figure G5 Effect of superficial air velocity and frother concentration on PGM grade keeping other factors at low levels (100g/t depressant and 18cm froth height)

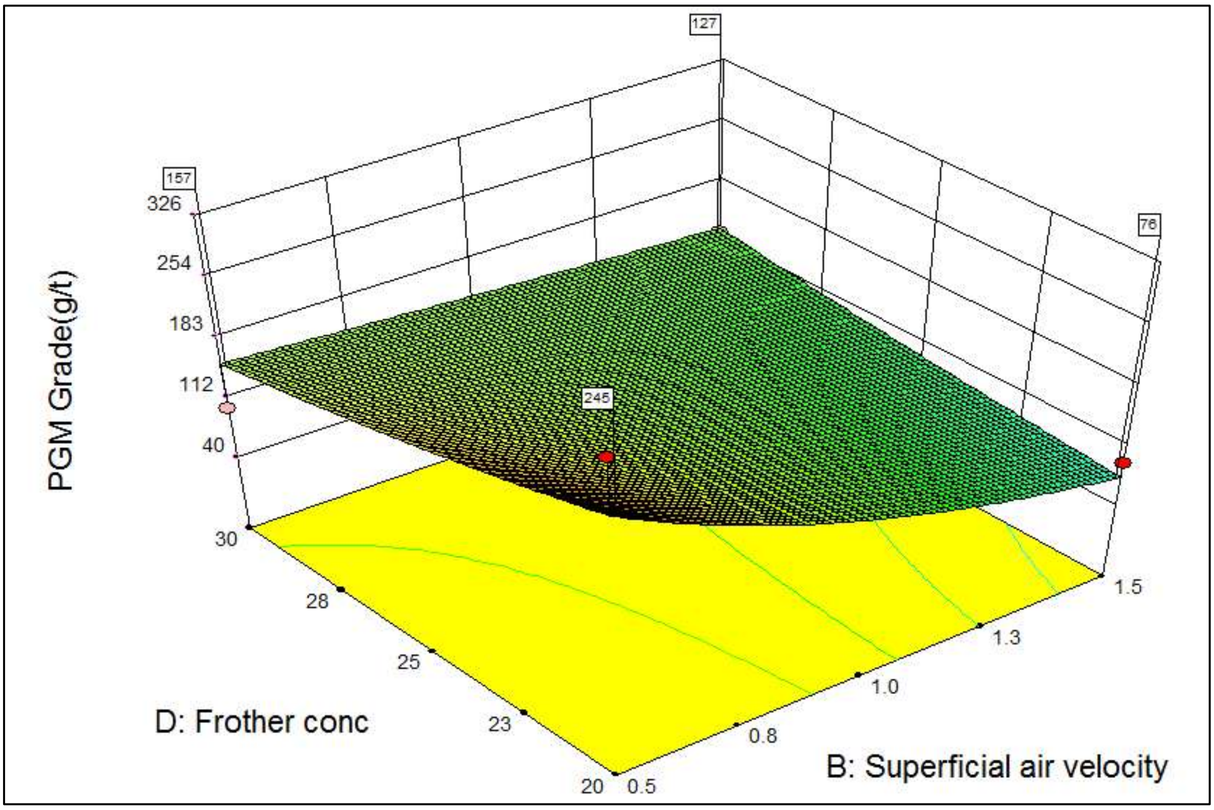


Figure G6 Effect of superficial air velocity and frother concentration on PGM grade keeping other factors at high levels (300g/t depressant and 30cm froth height)

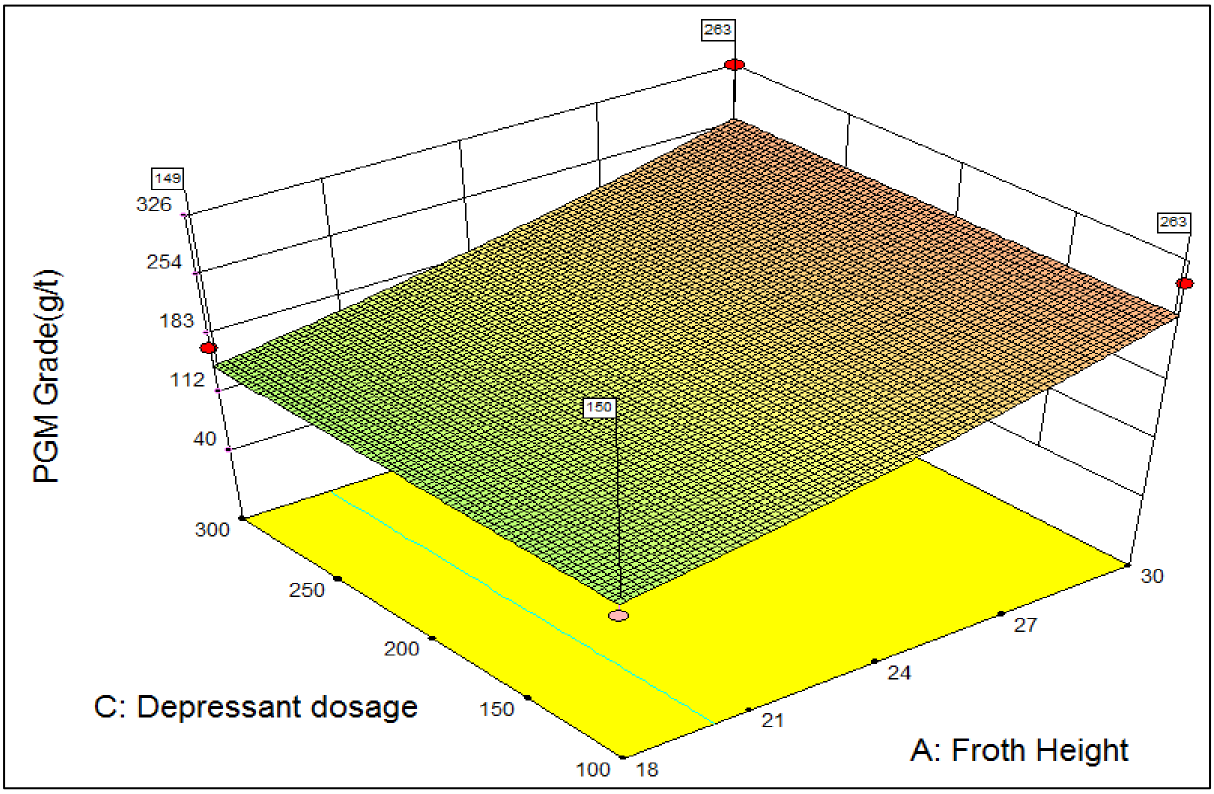


Figure G7 Effect of froth height and depressant dosage on PGM grade keeping other factors at low levels (0.5cm/sec superficial air velocity and 20ppm frother)

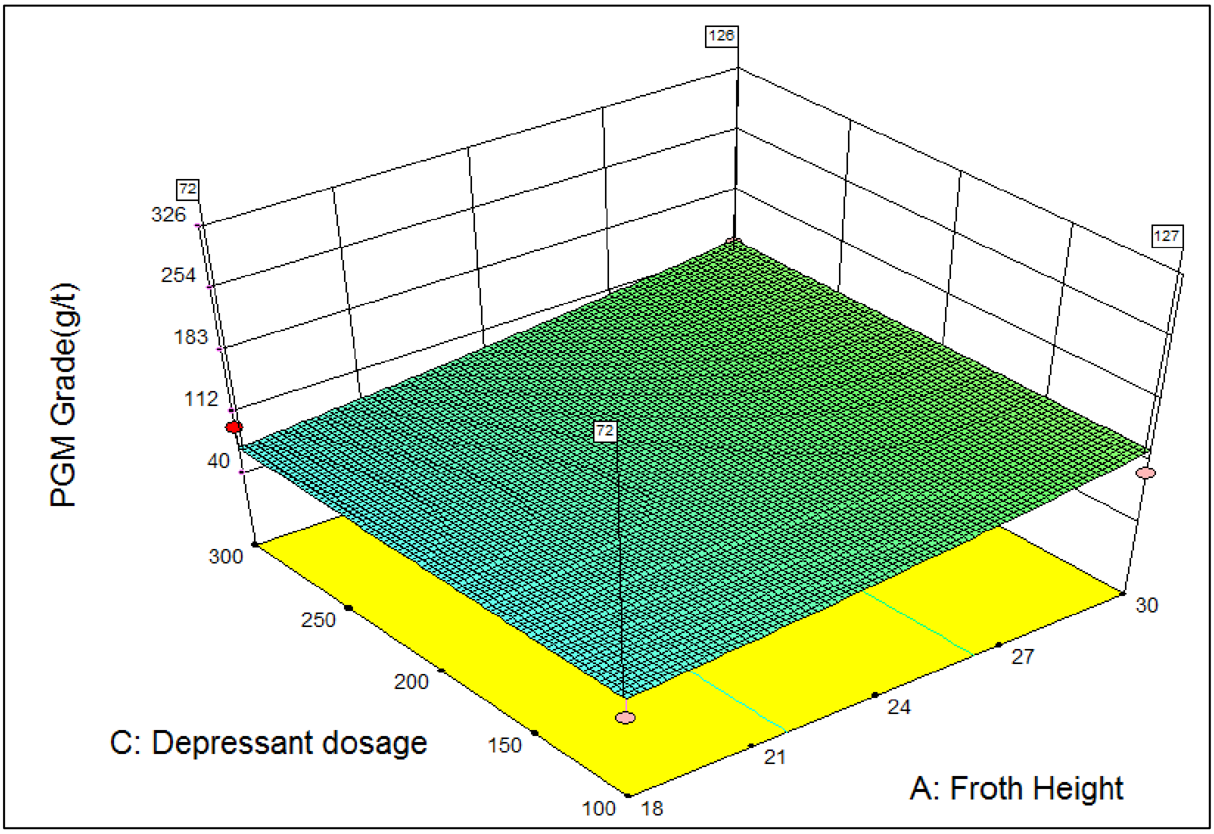


Figure G8 Effect of froth height and depressant dosage on PGM grade keeping other factors at high levels (1.5cm/sec superficial air velocity and 30ppm frother)