# CHAPTER 6

# RESULTS AND DISCUSSION FOR POWDER FACTOR (PF)

## 6.1 Results of PF estimation

Prior to discussing the chief objectives, it may be consequential to see the results of PF estimation (Table 6.1). From the results (quarry A, B and C), it is easily discernible that there exists a discrepancy between the actual and theoretical values of PF.

**Table 6.1: Discrepancy in theoretical and actual PF**

| S.No. | Quarry | Average PF (Theoretical) (Kg/t) | Average PF (Actual) (Kg/t) | Average % Discrepancy | Average standard deviation |
|---|---|---|---|---|---|
| 1. | A | 0.20 | 0.19 | 7.1 | 0.009 |
| 2. | B | 0.16 | 0.14 | 9.4 | 0.008 |
| 3. | C | 0.23 | 0.21 | 9.4 | 0.011 |

For all the quarries, the theoretical PF is greater than the actual PF. The average % discrepancy has been observed as 7.1, 9.4 and 9.4 for the quarries A, B and C, respectively. the values of average standard deviation (0.009 for quarry A, 0.008 for quarry B and 0.011 for quarry C) have revealed correctness of the average PF (actual) value.

The values of theoretical PF and actual PF for all the quarries (quarry A, B and C) is illustrated individually in Appendix- A.1, A.2 and A.3 respectively. In the present study the actual PF values have been investigated instead of the theoretical PF values.

The primary descriptive statistics of the input blasting design parameters and an output parameter (PF) together with their respective symbols has been represented in Table 5.1.

## 6.2 Results from PCA

### 6.2.1 Results for quarry A using PCA

PCA led to the generation of 6 PC groups with eigen value greater than 1.0, which is illustrated by scree plot in Figure 6.1. These 6 PC groups accounted for 87.194% cumulative variance in blasting design parameters. Table 6.2 illustrates the data matrix explaining the variance and the number of PC groups.

**Table 6.2: Data matrix explaining variance for the study quarry A (for PF prediction)**

| Principal Component Group | Initial Eigenvalues and Variance | | |
|---|---|---|---|
| | Total | % of Variance | Cumulative % |
| 1 | **5.578** | 29.357 | 29.357 |
| 2 | **3.368** | 17.729 | 47.085 |
| 3 | **2.668** | 14.041 | 61.127 |
| 4 | **2.278** | 11.992 | 73.119 |
| 5 | **1.512** | 7.957 | 81.075 |
| 6 | **1.105** | 6.119 | **87.194** |
| 7 | .854 | 5.274 | 92.468 |
| 8 | .637 | 3.353 | 95.821 |
| 9 | .455 | 2.396 | 98.217 |
| 10 | .245 | 1.287 | 99.504 |
| 11 | .059 | .308 | 99.812 |
| 12 | .020 | .105 | 99.917 |
| 13 | .009 | .050 | 99.967 |
| 14 | .003 | .014 | 99.981 |
| 15 | .002 | .010 | 99.992 |
| 16 | .001 | .005 | 99.997 |
| 17 | .001 | .003 | 100.000 |
| 18 | 6.258E-005 | .000 | 100.000 |
| 19 | -1.002E-015 | -5.271E-015 | 100.000 |
| 20 | -1.003E-019 | -5.128E-015 | 100.000 |

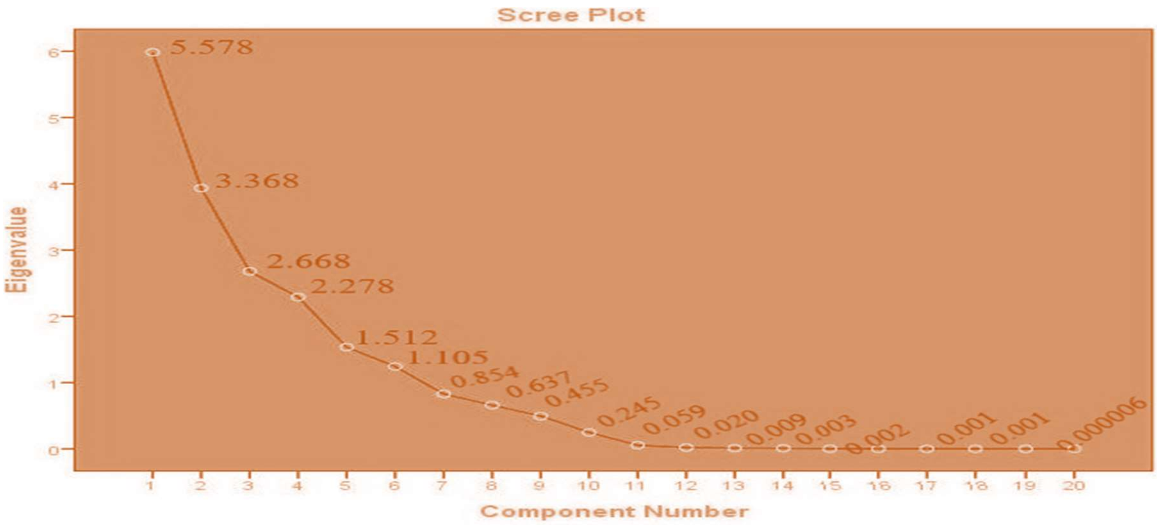


**Figure 6.1: Scree plot indicating principal component groups for PF in quarry A**

Table 6.3 illustrates the 6 PC groups with the coefficient of determination ($R^2$) values for all the blasting design parameters. As such, PCs were identified from each component group based on the value of $R^2$.

**Table 6.3: Identification of PCs in the study quarry A for PF**

| Blasting design parameters | PC groups with regression scores | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| B | .874 | -.346 | -.174 | .150 | .038 | -.174 |
| D | .723 | -.220 | -.067 | .219 | .318 | .244 |
| S | .850 | -.235 | -.162 | .144 | -.084 | -.204 |
| H | -.189 | .201 | -.650 | -.160 | .542 | -.149 |
| T | -.402 | -.112 | .081 | .458 | .686 | -.340 |
| CCL | .021 | .274 | -.838 | -.421 | .196 | .029 |
| S/B | -.500 | .433 | .137 | -.087 | -.273 | .047 |
| T/B | -.884 | .234 | .186 | .102 | .315 | .025 |
| H/B | -.841 | .387 | -.138 | -.184 | .210 | .137 |
| T/CCL | -.251 | -.262 | .657 | .566 | .245 | -.227 |
| Nr | .322 | .986 | .190 | .176 | .056 | .085 |
| Nh | .292 | .904 | .173 | .161 | .009 | .091 |
| Qe | .534 | .978 | .075 | .222 | .055 | .133 |
| Di | .478 | .177 | .514 | -.586 | .282 | -.084 |
| CPD | .740 | -.243 | -.136 | .149 | .259 | .214 |
| HD | .169 | -.205 | .160 | -.035 | .303 | .614 |
| RD | -.121 | -.451 | .246 | -.144 | .169 | .679 |
| Vr | .994 | .658 | -.045 | .204 | .060 | -.077 |
| SD | .303 | .260 | .563 | -.643 | .218 | -.156 |
| PPV | -.333 | .281 | -.286 | .682 | -.143 | .266 |

A total number of 14 PCs were identified and extracted from the Table 6.4, namely RD, H/B, SD, T, HD, Qe, CCL, PPV, Nh, S, Vr, Nr, B and T/B. These 14 PCs have been grouped into 6 PC groups based on the $R^2$ values. The results of 6 PC groups is tabulated in Table 6.4.

**Table 6.4: The 6 identified PC groups by PCA for PF (quarry A)**

| | |
|---|---|
| Principal Component Group-1 | B, S,T/B,H/B, Vr |
| Principal Component Group -2 | Nr, Nh, Qe |
| Principal Component Group -3 | H |
| Principal Component Group -4 | SD, PPV |
| Principal Component Group -5 | T |
| Principal Component Group -6 | HD, RD |

The MLR analysis for PF prediction has been carried out for all the identified 14 PCs [RD, H/B, SD, T, HD, Qe, CCL, PPV, Nh, S,Vr, Nr, B and T/B], revealed multi-collinearity. Therefore, after eliminating the multi-collinearity, MLR analysis for PF prediction has been carried out for all the retained 9 PCs [RD, T, SD, S, CCL, HD, Qe, PPV and Vr].

Table 6.5 summarizes the MLR analysis results for all the identified 14 PCs. It is revealed that an acute multi-collinearity was associated with some of these PCs.

**Table 6.5: MLR results for the identified 14 PCs**

| Model | R | R Square | Adjusted R Square | Significance | Std. Error of the Estimate |
|---|---|---|---|---|---|
| 1 | 0.912 | 0.831 | 0.794 | 0.00 | 0.011725 |

From the analysis, it has been found that 5 out of 14 PCs were having multi-collinearity (VIF>10). Therefore, 5 PCs were rejected because they contained multi-collinearity among input variables (Table 6.6).

**Table 6.6: Blast design parameters with multi-collinearity (VIF>10) for PF (quarry A)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | H/B | 16.12 |
| 2 | Nh | 13.15 |
| 3 | Nr | 11.16 |
| 4 | B | 13.25 |
| 5 | T/B | 14.13 |

Accordingly, the new prediction model has been developed after removing the 5 PCs, which contained multi-collinearity. As such, 9 PCs [RD, T, SD, S, CCL, HD, Qe, PPV and Vr] have been identified, which were free from multi-collinearity (Table 6.7).

**Table 6.7: Blast design parameters with multi-collinearity (VIF<10) for PF (quarryA)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | S | 3.242 |
| 2 | Qe | 2.696 |
| 3 | Vr | 7.244 |
| 4 | CCL | 1.286 |
| 5 | SD | 2.454 |
| 6 | PPV | 2.465 |

The MLR technique has thus been applied on the 6 identified parameters to develop the equation, subsequently the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error have been derived. Table 6.8 presents the results in terms of the unstandardized coefficients with the significance, standard error and collinearity statistics of the selected blasting design parameters.

**Table 6.8: Descriptive statistics of 6 parameters for developing predictor Eq. for PF**

| Blasting design parameters | Unstandardized Coefficients | | Significance | Collinearity Statistics | |
|---|---|---|---|---|---|
| | B | Std. Error | | Tolerance | VIF |
| (Constant) | .394 | .055 | .000 | | |
| S | -.029 | .006 | .000 | .308 | 3.242 |
| Qe | .005 | .000 | .000 | .479 | 2.696 |
| Vr | -2.970E-005 | .000 | .000 | .158 | 7.244 |
| CCL | .002 | .003 | .501 | .777 | 1.286 |
| SD | 5.554E-005 | .000 | .679 | .407 | 2.454 |
| PPV | -.001 | .002 | .732 | .406 | 2.465 |

The developed model in the form of equation using unstandardized regression coefficient (β-value) associated with 6 retained PCs (as illustrated in Table 6.8), is presented in Eq.6.1:

$$PF = 0.394 - S \times (0.029) + Qe \times (0.005) - Vr \times (0.000002970) + CCL \times (0.002) + SD \times (0.000005554) - PPV \times (0.001) \quad \textbf{(6.1)}$$

The MLR analysis results for the developed equation has been presented in Table 6.9.

**Table 6.9: MLR based descriptive statistics for the parameters used in Eq. 6.1**

| Model | R | R Square value | Adjusted R Square value | Significance level | Std. Error ofthe Estimate | F value |
|---|---|---|---|---|---|---|
| 1 | 0.885 | 0.783 | 0.764 | 0.00 | 0.01883 | 40.991 |

It is noteworthy that the value of $R^2$ is found to be 0.783 and adjusted ($R^2$) is 0.764 for the developed equation. The significance level was 0.00 and the F-value is 40.991, which strengthen the obtained results.

6.3.2 Results for quarry B using PCA

PCA led to the generation of 6 PC groups with eigen value greater than 1.0, which is illustrated by scree plot in Figure 6.2. These 6 PC groups and accounted for 90.95% cumulative variance in blasting design parameters. Table 6.10 illustrates the data matrix explaining the variance and the number of PC groups.

**Table 6.10: Data matrix explaining variance for the study quarry B (for PF prediction)**

| Principal Component Group | Initial Eigenvalues and Variance | | |
|---|---|---|---|
| | Total | % of Variance | Cumulative % |
| 1 | **6.755** | 33.773 | 33.773 |
| 2 | **3.469** | 17.343 | 51.116 |
| 3 | **2.676** | 13.379 | 64.494 |
| 4 | **1.833** | 9.166 | 73.660 |
| 5 | **1.339** | 6.694 | 80.354 |
| 6 | **1.016** | 5.517 | **85.872** |
| 7 | 0.946 | 5.079 | 90.950 |
| 8 | .581 | 2.907 | 93.858 |
| 9 | .497 | 2.486 | 96.344 |
| 10 | .336 | 1.681 | 98.024 |
| 11 | .137 | .687 | 98.712 |
| 12 | .113 | .567 | 99.278 |
| 13 | .105 | .527 | 99.805 |
| 14 | .018 | .091 | 99.896 |
| 15 | .009 | .044 | 99.940 |
| 16 | .005 | .024 | 99.964 |
| 17 | .004 | .019 | 99.982 |
| 18 | .001 | .006 | 99.996 |
| 19 | .001 | .004 | 100.000 |
| 20 | .001 | .003 | 100.000 |

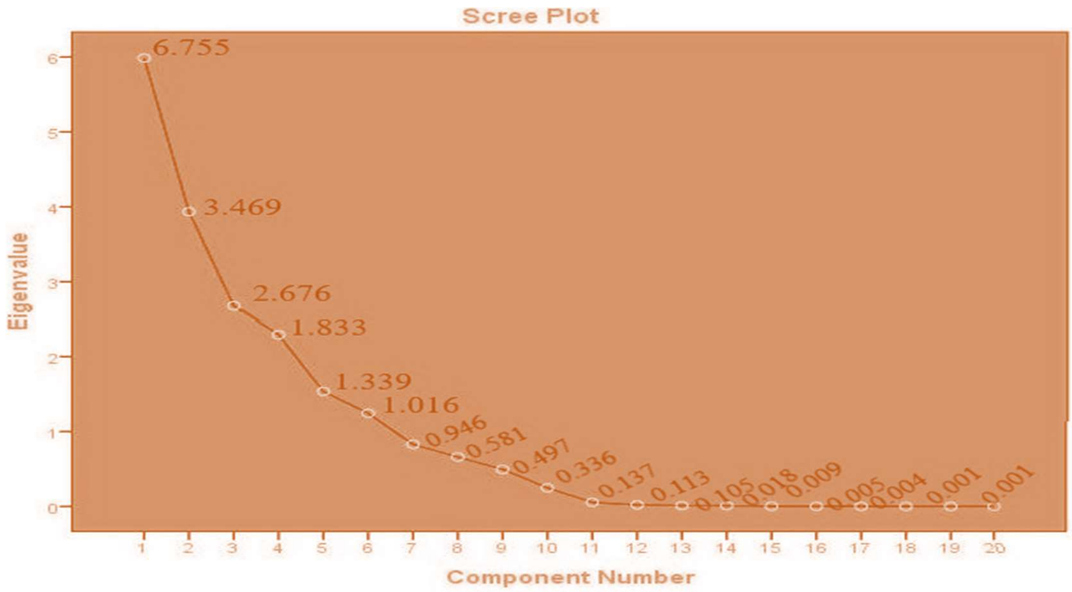


**Figure 6.2: Scree plot indicating principal component groups for PF in quarry B**

Table 6.11 illustrates the 6 PC groups with the coefficient of determination ($R^2$) values for all the blasting design parameters. As such, the PCs were identified from each component group based on the value of $R^2$.

**Table 6.11: Identification of PCs in study quarry B for PF**

| Blasting design parameters | PC Groups with regression coefficient | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| B | .986 | .007 | -.028 | .100 | -.026 | .016 |
| D | .960 | .086 | -.056 | .028 | .053 | -.015 |
| S | .941 | -.082 | .005 | .099 | -.027 | .185 |
| H | .140 | .216 | .361 | -.377 | .185 | .686 |
| T | .271 | .843 | -.189 | -.377 | -.078 | .153 |
| CCL | -.194 | -.770 | .425 | .162 | .193 | .253 |
| S_B | -.316 | -.307 | .047 | -.063 | -.010 | .512 |
| T_B | -.904 | .466 | -.092 | -.299 | .005 | .063 |
| H_B | -.969 | .021 | .081 | -.145 | .057 | .089 |
| T_CCL | .250 | .846 | -.303 | -.310 | -.126 | .005 |
| Nr | -.229 | .281 | .886 | .026 | -.110 | -.143 |
| Nh | -.293 | .287 | .805 | .158 | -.119 | -.184 |
| Qe | .138 | .359 | .816 | -.019 | -.012 | .000 |
| Di | .025 | .553 | -.045 | .748 | -.059 | .175 |
| CPD | .954 | -.007 | .003 | .056 | .089 | .022 |
| HD | .034 | .440 | .176 | .184 | .664 | -.050 |
| RD | .001 | .154 | -.045 | -.044 | .863 | -.170 |
| Vr | .740 | .130 | .806 | .211 | -.122 | .088 |
| SD | -.643 | .481 | -.034 | .542 | -.100 | .112 |
| PPV | .300 | -.150 | .534 | -.623 | -.062 | -.232 |

A total number of 15 PCs were identified and extracted from the Table 6.11, namely H, Di, RD, H/B, Nr, T/CCL,Qe, Nh, CPD, S, Vr, T/B, D, B and T. These 15 PCs have been grouped into 6 PC groups based on the $R^2$ values. The results of 6 PC groups is tabulated in Table 6.12.

**Table 6.12: The 6 identified PC groups by PCA for PF (quarry B)**

| | |
|---|---|
| Principal Component Group-1 | B, D, S, H/B, CPD, T/B |
| Principal Component Group -2 | T, T/CCL |
| Principal Component Group -3 | Qe, Nr, Nh, Vr |
| Principal Component Group -4 | Di |
| Principal Component Group -5 | RD |
| Principal Component Group -6 | H |

The MLR analysis for PF prediction carried out for all the identified 15 PCs [H, Di, RD, H/B, Nr, T/CCL, Qe, Nh, CPD, S, Vr, T/B, D, B and T], revealed multi-collinearity. Therefore, after eliminating the multi-collinearity, MLR analysis for PF prediction has been carried out for the retained 9 PCs [H, Di, RD, S, Nr, T/CCL, Qe, D, Vr], Table 6.13 summarizes the MLR analysis results for all the identified 15 PCs. It is revealed that an acute multi-collinearity was associated with some of these PCs.

**Table 6.13: MLR results for the identified 15 PCs**

| Model | R | R Square | Adjusted R Square | Significance value | Std. Error of the Estimate |
|---|---|---|---|---|---|
| 1 | 0.885 | 0.783 | 0.735 | 0.00 | 0.021669 |

From the analysis, it has been found that 6 out of 15 PCs were having multi-collinearity (VIF>10). Therefore, 6 PCs were rejected because they contained multi-collinearity among input variables (Table 6.14).

**Table 6.14: Blast design parameters with multi-collinearity (VIF >10) for PF (quarry B)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | H/B | 13.62 |
| 2 | Nh | 12.15 |
| 3 | CPD | 17.36 |
| 4 | T/B | 13.25 |
| 5 | B | 18.23 |
| 6 | T | 11.13 |

Accordingly, the new prediction equation has been developed after removing the 6 PCs, which contained multi-collinearity. As such, 9 PCs [H, Di, RD, S, Nr, T/CCL, Qe, D and Vr] have been selected, which were free from multi-collinearity (Table 6.15).

**Table 6.15: Blast design parameters without multi-collinearity (VIF <10) for PF (quarry B)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | D | 4.620 |
| 2 | S | 8.537 |
| 3 | Vr | 6.504 |
| 4 | T/CCL | 1.240 |
| 5 | Nr | 2.633 |
| 6 | Di | 1.231 |
| 7 | Qe | 1.717 |
| 8 | RD | 1.063 |
| 9 | H | 1.218 |

The MLR technique has thus been applied on the 9 identified parameters to develop the equation, subsequently the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error have been derived. Table 6.16 presents the results in terms of the unstandardized coefficients with the significance, standard error and collinearity statistics of the selected blasting design parameters.

**Table 6.16: Descriptive statistics of 9 parameters for developing predictor Eq. for PF**

| Blasting design parameters | Unstandardized Coefficients | | Significance level | Collinearity Statistics | |
|---|---|---|---|---|---|
| | B | Std. Error | | Tolerance | VIF |
| (Constant) | .278 | .147 | .063 | | |
| D | .001 | .000 | .000 | .216 | 4.620 |
| S | -.065 | .010 | .000 | .117 | 8.537 |
| Vr | -1.691E-006 | .000 | .649 | .154 | 6.504 |
| T/CCL | -.102 | .033 | .003 | .807 | 1.240 |
| Nr | .015 | .007 | .048 | .380 | 2.633 |
| Di | 2.784E-005 | .000 | .626 | .813 | 1.231 |
| Qe | 3.687E-005 | .000 | .002 | .582 | 1.717 |
| RD | .000 | .000 | .271 | .941 | 1.063 |
| H | .010 | .014 | .462 | .821 | 1.218 |

The developed model in the form of equation using unstandardized regression coefficient (β-value) associated with 9 retained PCs (as illustrated in Table 6.16), is presented in Eq.6.2:

$$PF = 0.278 + 0.001 \times (D) - 0.065 \times (S) - 0.000001691 \times (Vr) - 0.102 \times \left(\frac{T}{CCL}\right) + 0.015 \times (Nr) + 0.0000278 \times (Di) + 0.0000368 \times (Qe) + 0.010 \times (H) \qquad \mathbf{(6.2)}$$

The MLR analysis results for the developed equation has been presented in Table 6.17.

**Table 6.17: MLR based descriptive statistics for the parameters used in Eq. 6.2**

| Model | R | R Square | Adjusted RSquare | Significance level | Std. Error of the Estimate | F |
|---|---|---|---|---|---|---|
| 1 | 0.876 | 0.767 | 0.736 | 0.00 | 0.0216210 | 25.199 |

It is noteworthy that the value of $R^2$ has been found be 0.767 and adjusted $R^2$ has been found as 0.736 for the selected equation. The significance level has been found to be 0.00and the F-value has been observed as 25.199, which improves the authenticity of the predictor equation.

6.3.3 Results for quarry C using PCA

PCA led to the generation of 7 PC groups with eigen value greater than 1.0, which is illustrated by scree plot in Figure 6.3. These 7 PC groups accounted for 89.45 % cumulative variance in blasting design parameters. Table 6.18 illustrates the data matrix explaining the total variance and the number of PC groups.

**Table 6.18: Data matrix explaining variance for the study quarry C (for PF prediction)**

| Principal Component group | Initial Eigenvalues and variance | | |
|---|---|---|---|
| | Total | % of Variance | Cumulative % |
| 1 | **4.668** | 24.570 | 24.570 |
| 2 | **3.543** | 18.650 | 43.220 |
| 3 | **2.797** | 14.721 | 57.941 |
| 4 | **1.845** | 9.713 | 67.654 |
| 5 | **1.720** | 9.052 | 76.706 |
| 6 | **1.399** | 7.364 | 84.070 |
| 7 | **1.023** | 5.385 | **89.455** |
| 8 | .887 | 4.667 | 94.121 |
| 9 | .669 | 3.519 | 97.640 |
| 10 | .257 | 1.355 | 98.995 |
| 11 | .076 | .401 | 99.396 |
| 12 | .062 | .325 | 99.721 |
| 13 | .035 | .185 | 99.905 |
| 14 | .012 | .061 | 99.966 |
| 15 | .003 | .017 | 99.983 |
| 16 | .002 | .009 | 99.993 |
| 17 | .001 | .004 | 99.997 |
| 18 | .000 | .002 | 99.999 |
| 19 | .000 | .001 | 100.000 |
| 20 | .000 | .001 | 100.000 |

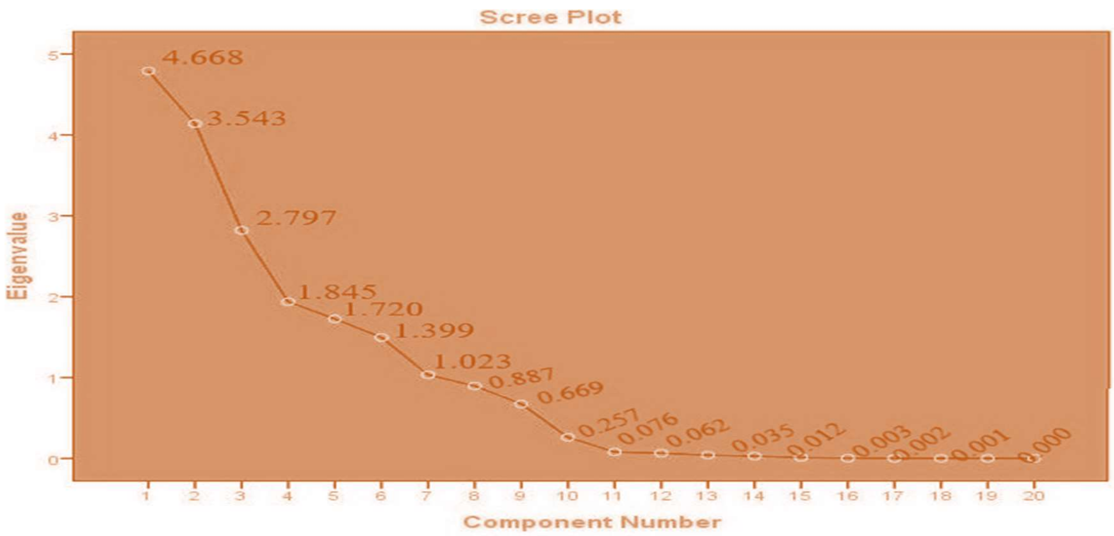


**Figure 6.3: Scree plot indicating principal component groups for PF in quarry C**

Table 6.19 illustrates the 7 PC groups with the coefficient of determination ($R^2$) values for all the blasting design parameters. As such, the PCs were identified from each component group based on the value of $R^2$.

**Table 6.19: Identification of PCs in the study quarry C for PF**

| Blasting design parameters | PC groups with regression coefficient | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| B | -.425 | .561 | -.141 | .181 | .595 | .226 | -.139 |
| D | -.070 | -.009 | .101 | -.559 | -.127 | .296 | .381 |
| S | -.105 | .491 | -.248 | -.067 | -.058 | .793 | -.160 |
| H | .569 | -.181 | .545 | -.151 | .407 | .129 | -.283 |
| T | .677 | -.529 | -.061 | .043 | .397 | .197 | -.123 |
| CCL | -.072 | .367 | .836 | -.235 | .107 | -.071 | -.207 |
| S/B | .321 | -.077 | -.116 | -.252 | -.662 | .552 | -.019 |
| T/B | .719 | -.680 | .022 | -.060 | .015 | .039 | -.030 |
| H/B | .633 | -.539 | .400 | -.220 | -.250 | -.113 | -.044 |
| T/CCL | .565 | -.569 | -.450 | .138 | .241 | .183 | .003 |
| Nr | .712 | .534 | .100 | .323 | -.182 | -.141 | .059 |
| Nh | .728 | .546 | .092 | .300 | -.178 | -.083 | .096 |
| Qe | .715 | .543 | .095 | .233 | -.158 | -.141 | .113 |
| CPD | -.120 | .328 | .881 | -.457 | .027 | .074 | .023 |
| Di | -.287 | -.382 | .575 | .555 | -.121 | .289 | .089 |
| HD | .140 | .143 | .057 | -.036 | .328 | .067 | .770 |
| RD | .333 | -.107 | .176 | -.084 | .470 | .192 | .231 |
| Vr | .507 | .735 | .119 | .286 | .060 | .242 | -.079 |
| SD | -.269 | -.432 | .450 | .643 | -.128 | .280 | .081 |
| PPV | .602 | .402 | -.364 | -.322 | .070 | -.027 | -.090 |

A total number of 12 PCs were identified and extracted from the Table 6.19, namely HD, T/B, SD, Vr,CPD, S/B, S, CCL, Qe, Nr, Nh and T/CCL, and are tabulated in Table 6.20.

**Table 6.20: The 7 identified PC groups by PCA for PF (quarry C)**

| | |
|---|---|
| Principal Component Group-1 | T/B, Nr, Nh, Qe |
| Principal Component Group -2 | Vr |
| Principal Component Group -3 | CCL, CPD |
| Principal Component Group -4 | D, SD |
| Principal Component Group -5 | S/B |
| Principal Component Group -6 | S |
| Principal Component Group - 7 | HD |

The MLR analysis for PF prediction carried out for all the identified 12 PCs [HD, T/B, SD, Vr, CPD, S/B, S, CCL, Qe, Nr,Nh and T/CCL], revealed multi-collinearity. Therefore, after eliminating multi-collinearity, MLR analysis for PF prediction has been carried out for the retained 8 PCs [HD, T/B, SD, Vr, CPD, S, CCL, Qe].

Table 6.21 summarizes the MLR analysis results for all the identified 12 PCs. It is revealed that an acute multi-collinearity was associated with some of these PCs.

**Table 6.21: MLR results for all the identified 12 PCs**

| Model | R | R Square | Adjusted R Square | Significance level | Std. Error of the Estimate |
|---|---|---|---|---|---|
| 1 | 0.933 | 0.871 | 0.835 | 0.00 | 0.008224 |

From the analysis, it has been found that 4 out of 12 PCs were having multi-collinearity (VIF>10). Therefore, 4 PCs were rejected because they contained multi-collinearity among input variables (Table 6.22).

**Table 6.22: Blast design parameters with multi-collinearity (VIF >10) for PF (quarry C)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | S/B | 14.25 |
| 2 | Nr | 11.36 |
| 3 | Nh | 15.12 |
| 4 | T/CCL | 12.36 |

Accordingly, the new prediction equation has been developed after removing the 4 PCs, which contained multi-collinearity. As such, 8 PCs [HD, T/B, SD, Vr, CPD, S, CCL, Qe] have been selected, which were free from multi-collinearity (Table 6.23).

**Table 6.23: Blast design parameters without multi-collinearity (VIF <10) for PF (quarry C)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | T/B | 2.237 |
| 2 | Qe | 6.525 |
| 3 | Vr | 8.889 |
| 4 | CPD | 3.976 |
| 5 | CCL | 4.560 |
| 6 | SD | 1.179 |
| 7 | S | 6.280 |
| 8 | HD | 1.043 |

The MLR technique thus been applied on the 8 identified parameters to develop the equation, subsequently the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error have been derived. Table 6.24 presents the results in terms of the unstandardized coefficients with the significance, standard error and collinearity statistics of the selected blasting design parameters.

**Table 6.24: Descriptive statistics of 8 parameters for developing predictor Eq. for PF**

| Model | Unstandardized Coefficients | | Significance level | Collinearity Statistics | |
|---|---|---|---|---|---|
| | B | Std. Error | | Tolerance | VIF |
| (Constant) | .210 | .046 | .000 | | |
| T/B | -.020 | .010 | .045 | .447 | 2.237 |
| Qe | .006 | .000 | .000 | .153 | 6.525 |
| Vr | -1.312E-005 | .000 | .000 | .112 | 8.889 |
| CPD | .000 | .001 | .765 | .252 | 3.976 |
| CCL | .003 | .006 | .609 | .219 | 4.560 |
| SD | 5.742E-005 | .000 | .739 | .848 | 1.179 |
| S | .023 | .008 | .007 | .159 | 6.280 |
| HD | -.001 | .001 | .535 | .959 | 1.043 |

The developed model in the form of equation using unstandardized regression coefficient (β-value) associated with 6 retained PCs (as illustrated in Table 6.24), is presented in Eq.6.3:

$$PF = 0.210 - 0.020 \times \left(\frac{T}{B}\right) + 0.006 \times (Qe) - 0.000001312 \times (Vr) + 0.003 \times (CCL) + 0.000005742 \times (SD) - 0.023 \times (S) - 0.001 \times (HD) \quad \textbf{(6.3)}$$

The MLR analysis results for the developed equation have been presented in Table 6.25.

**Table 6.25: MLR based descriptive statistics for the parameters used in Eq. 6.3**

| Model | R | R Square | Adjusted R Square | Significance level | Std. Error of the Estimate | F |
|---|---|---|---|---|---|---|
| 1 | 0.930 | 0.865 | 0.842 | 0.00 | 0.008042 | 38.995 |

The value of ($R^2$) is 0.865 and adjusted ($R^2$) is 0.842 for the selected equation. The significance level has been found to be 0.00, and the F-value has been found as 38.995, which improves the authenticity of the predictor equation.

## 6.4 Results from SSE technique

### 6.4.1 Results for quarry A using SSE

The correlation matrix in Table 6.26 presents the significance values of all the blasting design parameters with their respect to PF and Sig. (2-tailed).

**Table 6.26: Correlation matrix with significance values with respect to PF (quarry A)**

| Blasting design Parameters | PF | Significance |
|---|---|---|
| | Pearson correlation | (2-tailed) |
| B | -0.545 | 0.000 |
| D | 0.038 | 0.025 |
| S | -0.520 | 0.000 |
| H | -0.185 | 0.111 |
| T | 0.160 | 0.271 |
| CCL | 0.108 | 0.782 |
| S/ B | 0.373 | 0.001 |
| T/ B | 0.409 | 0.000 |
| H/ B | 0.454 | 0.000 |
| T/CCL | -0.015 | 0.899 |
| Nr | 0.540 | 0.000 |
| Nh | 0.515 | 0.002 |
| Qe | 0.568 | 0.000 |
| Di | 0.140 | 0.230 |
| CPD | 0.026 | 0.025 |
| Vr | 0.402 | 0.000 |
| HD | 0.053 | 0.654 |
| RD | 0.052 | 0.661 |
| PPV | 0.253 | 0.028 |
| SD | 0.140 | 0.001 |

Nine parameters [ B, S, S/B, T/B, H/B, Nr, Nh, Qe and Vr] have been identified having sig. $\leq 0.05$, as revealed in Table 6.26. The results of MLR for PF prediction performed on the 9 identified parameters have been summarized in Table 6.27.

**Table 6.27: MLR results for predicting PF using the identified 9 parameters**

| Model | R value | R Square Value | Adjusted R Square value | Significance level | Std. Error of the Estimate |
|---|---|---|---|---|---|
| 1 | 0.895 | 0.801 | 0.767 | 0.00 | 0.010933 |

MLR analysis reveals Multi-collinearity in 5 out of 9 parameters. The values of VIF for the 5 parameters, which revealed multi-collinearity, are tabulated in Table 6.28.

**Table 6.28: Blast design parameters with multi-collinearity (VIF >10) for PF (quarry A)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | B | 15.64 |
| 2 | S | 11.29 |
| 3 | S/B | 12.85 |
| 4 | H/B | 10.91 |
| 5 | Nr | 16.27 |

Consequently, after removal of the 5 parameters exhibiting multi-collinearity, only the 4 parameters (T/B, Nh, Qe and Vr) identified having no multi-collinearity are summarized in Table 6.29.

**Table 6.29: Blast design parameters without multi-collinearity (VIF <10) for PF (quarry A)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | T/B | 5.379 |
| 2 | Nh | 9.914 |
| 3 | Qe | 1.619 |
| 4 | Vr | 2.383 |

As such, the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error are presented in Table 6.30. This table presents the unstandardized coefficients with the significance, standard error and collinearity statistics of the identified blasting design parameters.

**Table 6.30: Descriptive statistics of 4 parameters for developing predictor Eq. for PF**

| Blasting design parameters | Unstandardized Coefficients | | Significance | Collinearity Statistics | |
|---|---|---|---|---|---|
| | B | Std. Error | | Tolerance | VIF |
| (Constant) | .203 | .021 | .000 | | |
| T/B | -.018 | .019 | .333 | .186 | 5.379 |
| Nh | .001 | .000 | .001 | .101 | 9.914 |
| Qe | .004 | .000 | .000 | .494 | 1.619 |
| Vr | -3.733E-005 | .000 | .000 | .388 | 2.383 |

The developed model in the form of equation using unstandardized regression coefficient (β-value) associated with 4 retained PCs (as illustrated in Table 6.30), is presented in Eq.6.4:

$$PF = 0.203 + 0.018 \times \left(\frac{T}{B}\right) + 0.001 \times (Nh) + Qe \times (0.004) - 0.00000373 \times (Vr) \qquad \mathbf{(6.4)}$$

The MLR analysis results for the developed equation is presented in Table 6.31.

**Table 6.31: MLR based descriptive statistics for the parameters used in the Eq. 6.4**

| Model | R value | R Square value | Adjusted R Square value | Significance Level | Std. Error of the Estimate | F value |
|---|---|---|---|---|---|---|
| 1 | 0.855 | 0.730 | 0.702 | 0.00 | 0.021171 | 25.922 |

The value of $R^2$ has been found to be 0.730 and adjusted $R^2$ has been found as 0.702. Furthermore, the F-ratio has been found to be 25.922 which is much greater than 4 and the significance level was 0.00, which improves the authenticity of the predictor equation.

Since the 4 parameters were introduced sequentially, therefore it may be consequential to state that with the addition of each parameter, the value of $R^2$ increased from 0.354 to 0.730, as clearly revealed in Table 6.32.

**Table 6.32: Summary of models prepared by MLR using SSE for PF (quarry A)**

| Model | R value | R Square value | Adjusted R Square value | Significance Level | F value | Predictor constants |
|---|---|---|---|---|---|---|
| 1 | 0.595 | 0.354 | 0.304 | 0.005 | 18.269 | T/B |
| 2 | 0.689 | 0.474 | 0.425 | 0.001 | 19.298 | T/B+Nh |
| 3 | 0.768 | 0.589 | 0.526 | 0.000 | 23.648 | T/B+Nh+Qe |
| 4 | **0.855** | **0.730** | **0.702** | **0.000** | **25.922** | T/B+Nh+Qe+Vr |

### 6.4.2 Results for quarry B using SSE

The correlation matrix in Table 6.33 presents the results of significance values of all the blasting design parameters with respect to PF.

**Table 6.33: Correlation matrix with significance values with respect to PF (quarry B)**

| Blasting design parameters | PF | Significance level |
|---|---|---|
| | Pearson correlation | (2-tailed) |
| B | 0.674 | 0.000 |
| D | -0.515 | 0.000 |
| S | -0.736 | 0.000 |
| H | 0.038 | 0.742 |
| T | 0.476 | 0.001 |
| CCL | 0.202 | 0.000 |
| S/ B | 0.089 | 0.450 |
| T/ B | 0.581 | 0.000 |
| H/ B | 0.687 | 0.000 |
| T/CCL | -0.202 | 0.026 |
| Nr | 0.422 | 0.000 |
| Nh | 0.432 | 0.052 |
| Qe | 0.316 | 0.005 |
| Di | 0.513 | 0.001 |
| CPD | -0.493 | 0.000 |
| HD | 0.073 | 0.520 |
| RD | -0.067 | 0.969 |
| PPV | 0.094 | 0.412 |
| SD | -0.586 | 0.003 |
| Vr | 0.612 | 0.001 |

Eleven parameters [ B, D, S, T/B, H/B, CCL, Nr, SD, Qe, CPD and Vr] have been identified having sig. ≤ 0.05, as revealed from Table 6.33. The results of MLR for PF prediction has been performed on the 11 identified parameters have been summarized in Table 6.34

**Table 6.34: MLR results for predicting PF using the identified 11 parameters**

| Model | R | R Square | Adjusted R Square | Significance level | Std. Error of the Estimate |
|---|---|---|---|---|---|
| 1 | 0.876 | 0.767 | 0.721 | 0.00 | 0.02224 |

MLR analysis reveals multi-collinearity in 3 out of 11 parameters. The values of VIF for the 3 parameters, which revealed multi-collinearity, are tabulated in Table 6.35.

**Table 6.35: Blast design parameters with multi-collinearity (VIF >10) for PF (quarry B)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | B | 14.16 |
| 2 | D | 16.12 |
| 3 | H/B | 11.25 |

Consequently, after removal of the 3 parameters exhibiting multi-collinearity, only the 8 parameters [S, T/B, CCL,Nr, Qe, CPD, Vr and SD] identified having no multi-collinearity are summarized in Table 6.36.

**Table 6.36: Blast design parameters without multi-collinearity (VIF <10) for PF (quarry B)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | CCL | 1.966 |
| 2 | T/B | 6.151 |
| 3 | Qe | 1.769 |
| 4 | Nr | 2.634 |
| 5 | CPD | 5.175 |
| 6 | Vr | 6.447 |
| 7 | SD | 2.020 |
| 8 | S | 1.821 |

As such, the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error are presented in Table 6.37. This table presents the unstandardized coefficients with the significance, standard error and collinearity statistics of the identified blasting design parameters.

**Table 6.37: Descriptive statistics of 8 parameters for developing predictor Eq. for PF**

| Model | Unstandardized Coefficients | | Significance level | Collinearity Statistics | |
|---|---|---|---|---|---|
| | B | Std. Error | | Tolerance | VIF |
| (Constant) | .378 | .139 | .111 | | |
| CCL | .019 | .011 | .083 | .509 | 1.966 |
| T/B | .011 | .036 | .753 | .163 | 6.151 |
| Qe | 3.321E-005 | .000 | .005 | .565 | 1.769 |
| Nr | .014 | .008 | .060 | .380 | 2.634 |
| CPD | .001 | .000 | .000 | .193 | 5.175 |
| Vr | -7.986E-007 | .000 | .829 | .155 | 6.447 |
| SD | .000 | .000 | .649 | .495 | 2.020 |
| S | -.064 | .012 | .000 | .492 | 1.821 |

The developed model in the form of equation using unstandardized regression coefficient (β-value) associated with 8 retained PCs (as illustrated in Table 6.37), is presented in Eq.6.5:

$$PF = 0.378 + 0.019 \times (CCL) + 0.011 \times \left(\frac{T}{B}\right) + 0.0000332 \times (Qe) + 0.014 \times (Nr) + 0.001 \times (CPD) - 0.000007986 \times (Vr) - 0.064 \times (S) \qquad \mathbf{(6.5)}$$

The MLR analysis results for the developed equation has been presented in Table 6.38.

**Table 6.38: MLR based descriptive statistics for the parameters used in Eq. 6.5**

| Model | R | R Square | Adjusted R Square | Significance level | Std. Error of the Estimate | F |
|---|---|---|---|---|---|---|
| 1 | 0.868 | 0.751 | 0.724 | 0.00 | 0.0221011 | 26.635 |

A close perusal of the valueof $R^2$ has been found to be 0.751 and adjusted $R^2$ has been found as 0.724. Furthermore, the F-ratio has been found to be 26.635 which is much greater than 4 and significance level has been found as 0.00, which improves the authenticity of the predictor equation.

Since the 8 parameters were introduced sequentially. Therefore, it may be consequential to state that with the addition of each parameter, the value of $R^2$ increased from 0.159 to 0.751, as clearly revealed in Table 6.39.

**Table 6.39: Summary of models prepared by MLR using SSE for PF (quarry B)**

| Model | R | R Square | Adjusted R Square | Significance level | F | Predictor constants |
|---|---|---|---|---|---|---|
| 1 | 0.399 | 0.159 | 0.103 | 0.006 | 9.368 | S |
| 2 | 0.456 | 0.207 | 0.156 | 0.000 | 12.365 | S+T/B |
| 3 | 0.515 | 0.265 | 0.209 | 0.002 | 13.235 | S+T/B+CCL |
| 4 | 0.585 | 0.342 | 0.286 | 0.005 | 15.624 | S+T/B+CCL+Nr |
| 5 | 0.696 | 0.484 | 0.425 | 0.001 | 16.165 | S+T/B+CCL+Nr+Qe |
| 6 | 0.757 | 0.573 | 0.516 | 0.000 | 21.348 | S+T/B+CCL+Nr+Qe+CPD |
| 7 | 0.806 | 0.649 | 0.594 | 0.000 | 23.402 | S+T/B+CCL+Nr+Qe+CPD+Vr |
| 8 | **0.868** | **0.751** | **0.724** | **0.000** | **26.635** | S+T/B+CCL+Nr+Qe+CPD+Vr+SD |

6.4.3 Results for quarry C using SSE

The correlation matrix in Table 6.40 presents the result of significance [sig.(2-tailed)] values of all the blasting design parameters with respect to PF.

**Table 6.40: Correlation matrix with significance values with respect to PF (quarry C)**

| Blasting design parameters Parameters | PF | Significance |
|---|---|---|
| | Pearson's correlation | (2-tailed) |
| B | 0.701 | 0.000 |
| D | -0.005 | 0.971 |
| S | -0.539 | 0.000 |
| H | -0.086 | 0.494 |
| T | 0.020 | 0.872 |

| | | |
|---|---|---|
| CCL | -0.156 | 0.000 |
| S/ B | 0.169 | 0.003 |
| T/ B | 0.345 | 0.005 |
| H/ B | 0.499 | 0.000 |
| T/CCL | 0.098 | 0.435 |
| Nr | 0.230 | 0.006 |
| Nh | 0.231 | 0.001 |
| Qe | 0.369 | 0.003 |
| Di | -0.103 | 0.001 |
| CPD | 0.413 | 0.412 |
| HD | 0.061 | 0.630 |
| RD | 0.030 | 0.810 |
| PPV | 0.032 | 0.412 |
| SD | -0.015 | 0.554 |
| Vr | 0.785 | 0.001 |

Eight parameters [ B, S, T/B, H/B, CCL, Di, Qe and Vr] have been identified having sig. $\leq 0.05$, as revealed from Table 6.40. The results of the MLR for PF prediction performed on the 8 identified parameters have been summarized in Table 6.41.

**Table 6.41: MLR for predicting PF using the identified 8 parameters**

| Model | R | R Square | Adjusted R Square | Significance level | Std. Error of the Estimate |
|---|---|---|---|---|---|
| 1 | 0.933 | 0.870 | 0.849 | 0.00 | 0.0078706 |

MLR analysis reveals multi-collinearity in 2 out of 8 parameters. The values of VIF for the 2 parameters, which revealed multi-collinearity, are tabulated in Table 6.42.

**Table 6.42: Blast design parameters with multi-collinearity (VIF <10) for PF (quarry C)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | T/B | 16.25 |
| 2 | H/B | 19.12 |

Consequently, after removal of the 2 parameters exhibiting multi-collinearity, only the 6 parameters [B, S, CCL, Di, Qe and Vr] identified having no multi-collinearity are summarized in Table 6.43.

**Table 6.43: Blast design parameters without multi-collinearity (VIF >10) for PF (quarry C)**

| S.No. | Blasting design parameters | VIF values |
|---|---|---|
| 1 | B | 1.878 |
| 2 | S | 2.128 |
| 3 | CCL | 1.219 |
| 4 | Qe | 6.031 |
| 5 | Di | 1.202 |
| 6 | Vr | 7.651 |

As such, the unstandardized coefficients of the selected blasting design parameters together with their significance value and standard error are presented in Table 6.44. This table presents the unstandardized coefficients with the significance, standard error and collinearity statistics of the identified blasting design parameters.

**Table 6.44: Descriptive statistics of 6 parameters for developing predictor Eq. for PF**

| Model | Unstandardized Coefficients | | Significance level | Collinearity Statistics | |
|---|---|---|---|---|---|
| | B | Std. Error | | Tolerance | VIF |
| (Constant) | .187 | .040 | .764 | | |
| B | -.022 | .007 | .011 | .532 | 1.878 |
| S | .002 | .005 | .001 | .470 | 2.128 |
| CCL | .001 | .003 | .162 | .820 | 1.219 |
| Qe | .000 | .000 | .011 | .166 | 6.031 |
| Di | 7.821E-006 | .000 | .055 | .832 | 1.202 |
| Vr | -1.486E-005 | .000 | .083 | .131 | 7.651 |

The developed model in the form of equation using unstandardized regression coefficient (β-value) associated with 6 retained PCs (as illustrated in Table 6.44), is presented in Eq.6.6:

$$PF = 0.187 - 0.022 \times (B) + 0.002 \times (S) + 0.001 \times (CCL) + 0.00000782 \times (Di) - 0.000001486 \times (Vr) \quad \textbf{(6.6)}$$

The MLR analysis results for the developed equation has been presented in Table 6.45.

**Table 6.45: MLR based descriptive statistics for the parameters used in Eq. 6.6**

| Model | R | R Square | Adjusted R Square | Significance level | Std. Error of the Estimate | F |
|---|---|---|---|---|---|---|
| 1 | 0.904 | 0.818 | 0.795 | 0.00 | 0.0091632 | 36.529 |

A close perusal of the value of $R^2$ has been found to be 0.818 and adjusted $R^2$ has been found as 0.795. The significance level has been found to be 0.00 and F-ratio has been found as 36.529, which improves the authenticity of the predictor equation.

Since the 6 parameters were introduced sequentially, therefore it may be consequential to state that with the addition of each parameter, the value of $R^2$ increased from 0.425 to 0.818, as clearly revealed in Table 6.46.

**Table 6.46: Summary of models prepared by MLR using SSE for PF (quarry C)**

| Model | R | R Square | Adjusted R Square | Significance level | F | Predictor constants |
|---|---|---|---|---|---|---|
| 1 | 0.652 | 0.425 | 0.374 | 0.005 | 24.125 | B |
| 2 | 0.712 | 0.506 | 0.458 | 0.002 | 25.164 | B+S |
| 3 | 0.784 | 0.614 | 0.556 | 0.005 | 29.568 | B+S+CCL |
| 4 | 0.851 | 0.724 | 0.659 | 0.003 | 31.112 | B+S+CCL+Di |
| 5 | 0.858 | 0.736 | 0.688 | 0.000 | 31.256 | B+S+CCL+Di+Qe |
| 6 | **0.904** | **0.818** | **0.795** | **0.000** | **36.529** | B+S+CCL+Di+Qe+Vr |

**6.5 Results of validation and verification**

This section comprises two part, one is validation and another is verification.

6.5.1 Validation results

The validation of the developed equation with the different data set of the corresponding quarries has been done within statistical domain. The data set for validation and are illustrated in Appendix-A.4, A.5 and A.6. The results of this validation are described in the following sections:

*(i) Results of validation of developed equation for the PF (Quarry A)*

The results of computed values of PF by PCA and SSE methods are distinctly illustrated in form of bar chart (Figure 6.4).

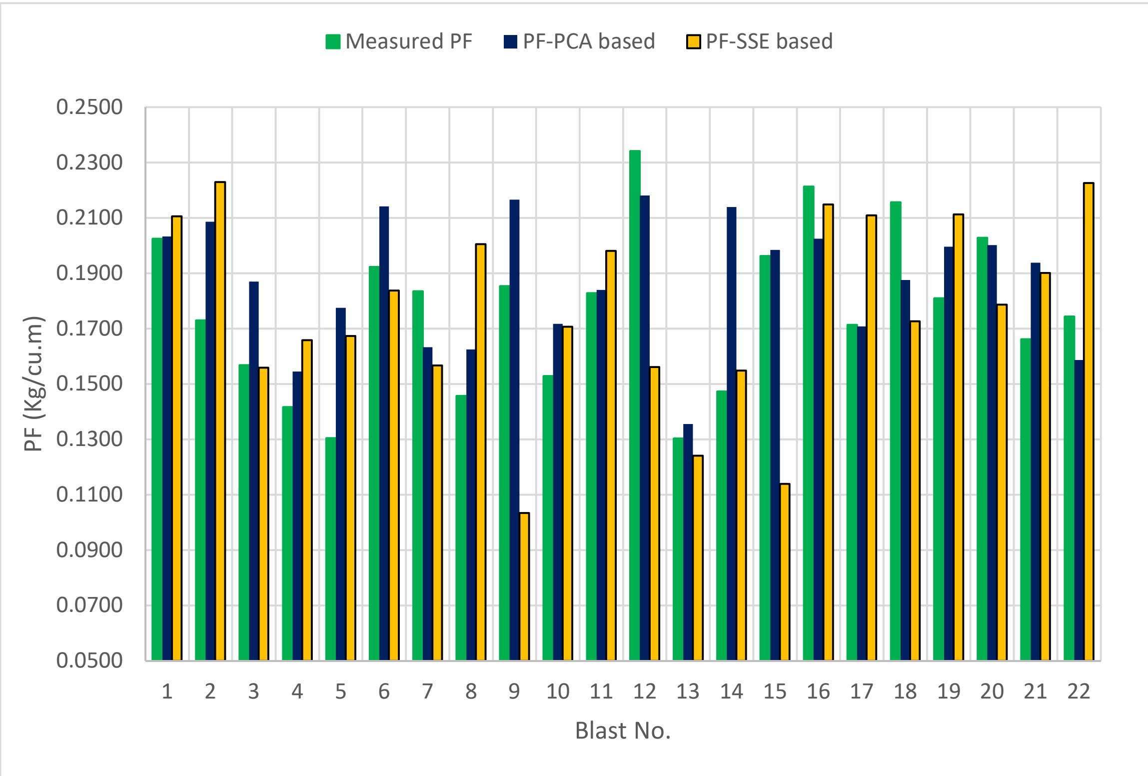


**Figure 6.4: Comparison of measured and Predicted PF Values for quarry A.**

The value of PF obtained using PCA equation lies between 0.14 Kg/t – 0.21 Kg/t, and the value of PF obtained using SSE equation lies between to be 0.11 Kg/t – 0.22 Kg/t.

The average standard deviation for the predicted value of PF by PCA analysis has been found to be 0.01. However, for SSE analysis the average standard deviation has been found to be 0.02, which is higher than that of PCA. Therefore, the values obtained by the PCA technique appear to be more precise as compare to SSE technique. This reveals the better authenticity of PCA in prediction of PF. This, in turn, validates the precision of the developed equations and this validation has set a high level of statistical assurance on the predictor Eq. 6.1 for the given study quarry.

*(ii) Results of validation of developed equation for the PF (Quarry B)*

The results of computed values of PF by PCA and SSE techniques are distinctly illustrated in form of bar chart (Figure 6.5).

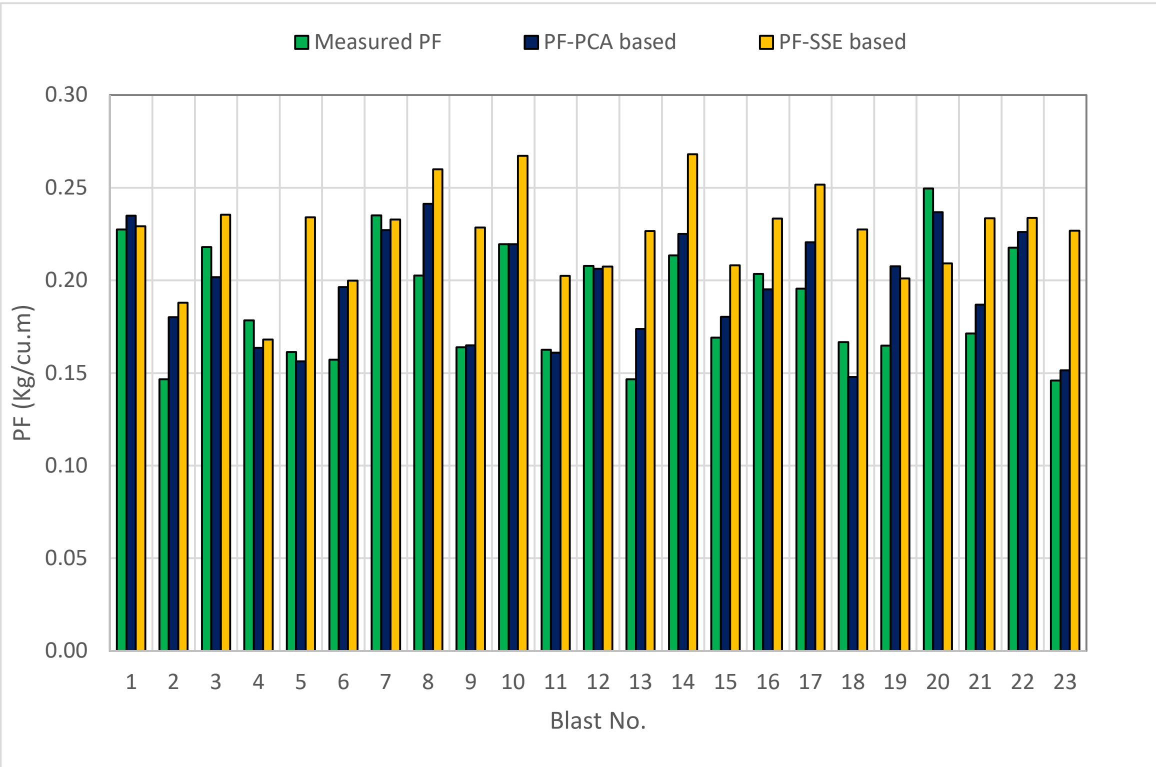


**Figure 6.5: Comparison of measured and predicted PF values for quarry B**

The value of PF obtained using PCA equation lies between 0.15 Kg/t – 0.24 Kg/t, and the value of PF obtained using SSE equation lies between to be 0.17 Kg/t – 0.25 Kg/t.

The average standard deviation for the predicted value of PF by PCA analysis has been found to be 0.01. However, for SSE analysis the average standard deviation has been found to be 0.02, which is higher than that of PCA. Therefore, the values obtained by the PCA technique appear to be more precise as compared to SSE technique. This, in turn, validates the precision of the developed equations and this validation has set a high level of statistical assurance on the predictor Eq. 6.2 for the given study quarry.

*(iii) Results of validation of developed equation for the PF (Quarry C)*

The results of computed values of PF by PCA and SSE techniques are distinctly illustrated in form of bar chart (Figure 6.6).

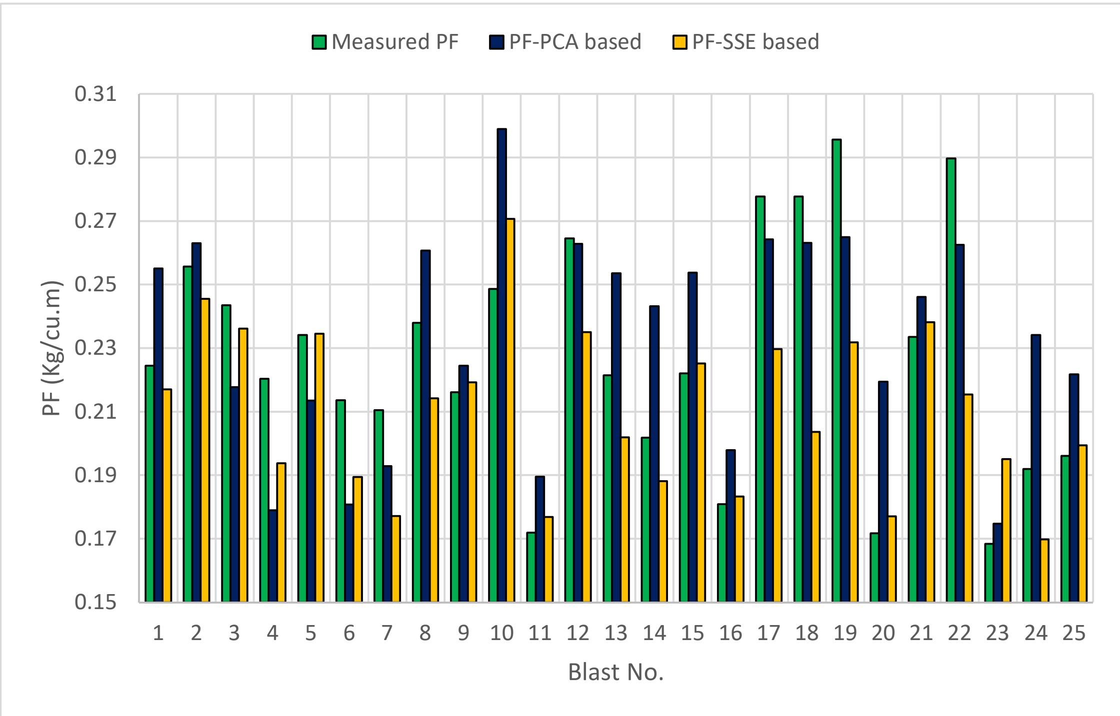


**Figure 6.6: Comparison of measured and predicted PF values for quarry C**

The value of PF obtained using PCA equation lies between 0.18 Kg/t – 0.26 Kg/t, and the value of PF obtained using SSE equation lies between to be 0.17 Kg/t – 0.27 Kg/t.

The average standard deviation for the predicted value of PF by PCA analysis has been found to be 0.01. However, for SSE analysis the average standard deviation has been found to be 0.02, which is higher than that of PCA. Therefore, the values obtained by the PCA technique are appear to be more precise as compared to SSE technique. This, in turn, validates the precision of the developed equations and this validation has set a high level of statistical assurance on the predictor Eq. 6.3 for the given study quarry.

### 6.5.2 Verification

*(i) Multilayer perceptron model (ANN) for verification of PF (Quarry A)*

To carry out the MLP neural network analysis, eight parameters were selected which has been identified using both PCA and SSE techniques. The identified parameters are Spacing (S),Stemming/Burden (T/B), No. of Holes (Nh), Scaled distance (SD), Column charge length (CCL), Total amount of explosive (Qe), Volume of rock (Vr) and Peak particle velocity (PPV). These parameters have been feed as input and the PF as output.

The network topology to predict the outcome (PF), consists of three layer (Input, hidden and output layer). In the input layer, there are eight input neurons, in the hidden layer, there are four neurons and one output neurons. The model summary indicated in Table 6.47, provides information related to the results of training and testing samples. Sum of square error is given for both training and testingsample. The small value (0.250) of the error related to training sample indicates the power of the model to predict the outcome. According to the Table 6.48, the Sum of squared error is 0.250 for training and 1.679 for testing samples.

**Table 6.47: Model Summary for PF using ANN (quarry A)**

| Model Summary for MLP | | |
|---|---|---|
| **Training** | Correlation value | 0.932 |
| | Sum of Squares Error | 0.250 |
| | Relative Error | .011 |
| | Stopping Rule Used | 1 consecutive step(s) with no decrease in error |
| | Training Time | 0:00:00.01 |
| **Testing** | Correlation value | 0.940 |
| | Sum of Squares Error | 1.679 |
| | Relative Error | .179 |

The graph between measured value of PF and predicted value by ANN technique has been plotted as shown in Figure 6.7. The value of coefficient of determination ($R^2$) was found to be 0.941, which indicates the high degree of correlation of blasting design parameters with the PF.

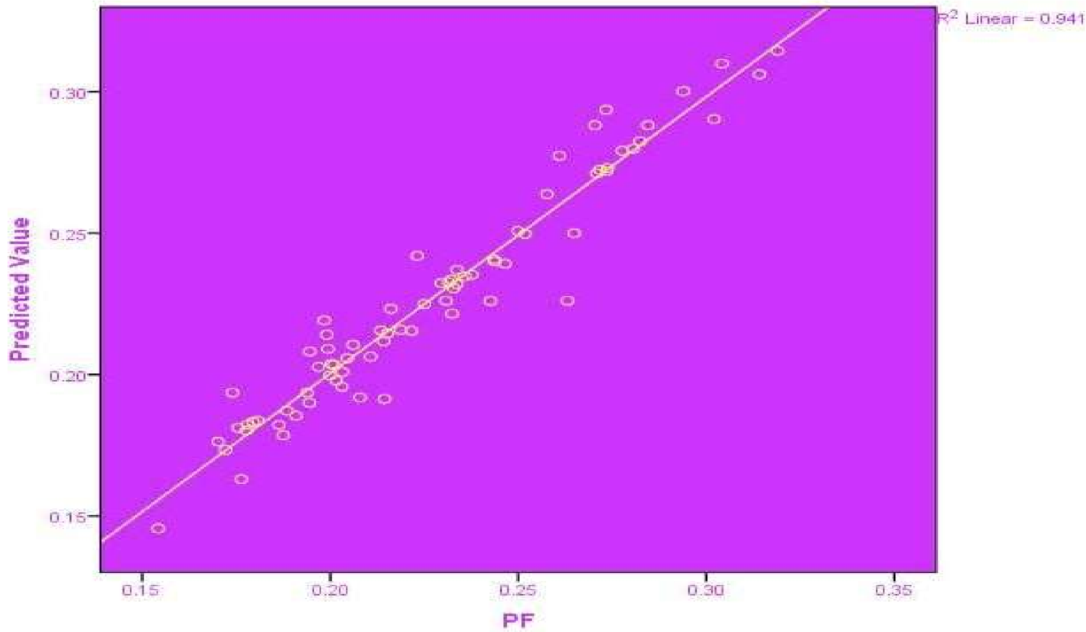


**Figure 6.7: Plot between measured and predicted value of PF by ANN technique (quarry A)**

The MLP neural network model also gives the information about the impact of each independent variable in terms of normalized importance. Figure 6.8 indicates the importanceof the variables.

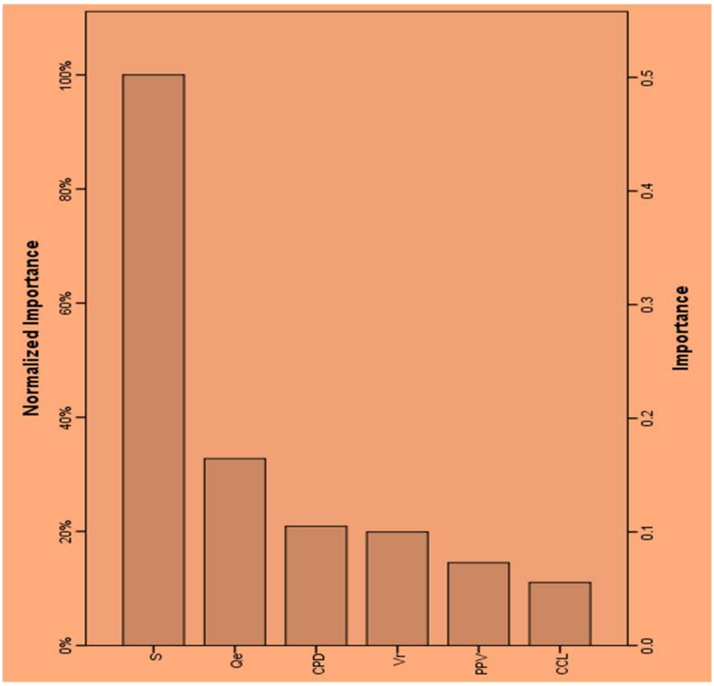


**Figure 6.8: Independent variables importance chart for PF (quarry A)**

*(ii) Multilayer perceptron model for verification of PF (Quarry B)*

To carry out the MLP neural network analysis, eleven parameters were selected which have been identified using PCA and SSE techniques. The parameters identified are Diameter of hole (D), Spacing (S), Hole depth (H), Column charge length (CCL), Stemming/ Burden ratio (T/B),Stemming/ Column charge length ratio (T/CCL), No. of rows (Nr), Total amount of explosive (Qe), Distance (Di), Charge per delay (CPD) and Volume of rock (Vr).

The network topology to predict the outcome (PF), consists of three layer (Input, hidden and output layer). In the input layer, there are eleven input neurons, in the hidden layer, there are five neurons and one output neurons. The model summary indicated in Table 6.49, presents information related to the results of training and testing samples. Sum of square error is given for both training and testingsample.

The small value (6.231) of the error related to training sample indicates the power of the model to predict the outcome. According to the Table 6.48, the Sum of squared errors(SSE) is 6.231 for training and 3.821 for testing samples.

**Table 6.48: Model Summary of PF using ANN (quarry B)**

| Model Summary for MLP | | |
|---|---|---|
| **Training** | Correlation value | 0.953 |
| | Sum of Squares Error | 6.231 |
| | Relative Error | .254 |
| | Stopping Rule Used | 1 consecutive step(s) with no decrease in error |
| | Training Time | 0:00:00.02 |
| **Testing** | Correlation value | 0.965 |
| | Sum of Squares Error | 3.821 |
| | Relative Error | .365 |

The graph between measured value of PF and predicted value by ANN technique has been plotted as shown in Figure 6.9. The value of coefficient of determination ($R^2$) was found tobe 0.966, which indicates the high degree of correlation of blasting design parameters with the PF.

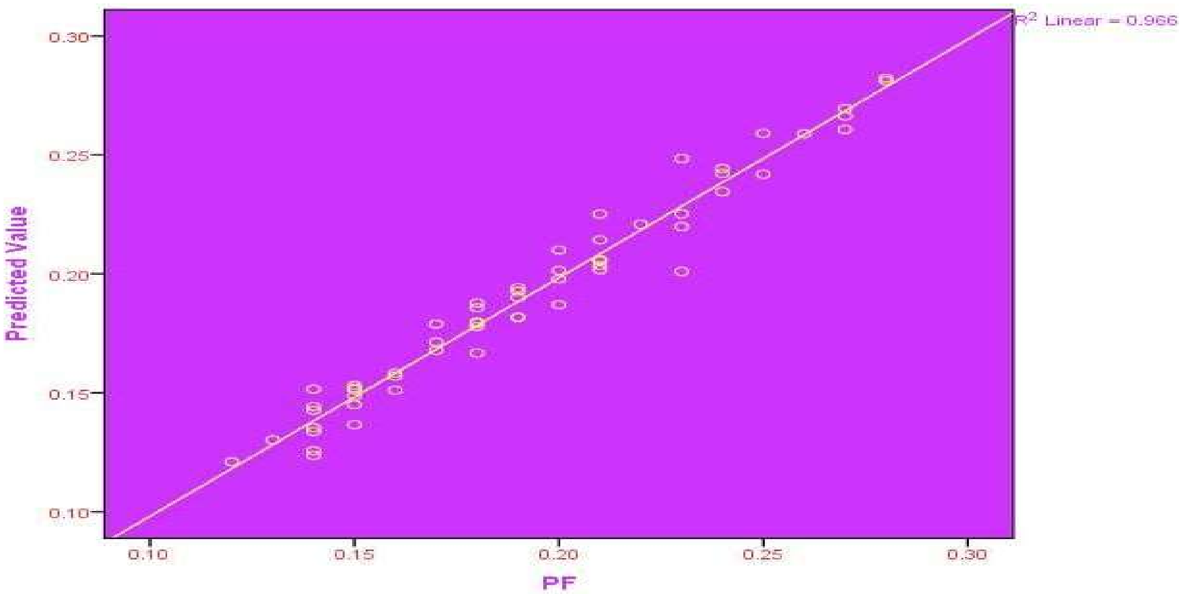


**Figure 6.9: Plot between measured and predicted value of PF by ANN technique (quarry B).**

The MLP neural network model also gives the information about the impact of each independent variable in terms of normalized importance. Figure 6.10 indicates the importanceof the variables.

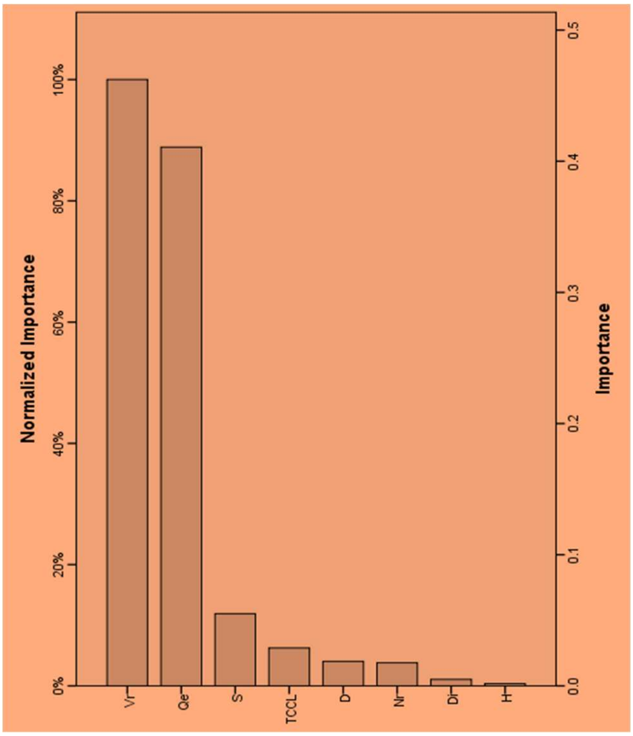


**Figure 6.10: Independent variable importance chart for PF (Quarry B)**

It is evident from the Figure that in MLP technique, the most important parameters are Volume of rock (Qe) and Total amount of explosive (Qe), which have influencing the PF with 100% and 90% extent. Six parameters namely, Spacing (S), Stemming/column charge length (T/CCL), diameter of hole (D), number of holes (Nh), distance (Di) and and hole depth (H) have influencing the PF with 12%, 7%, 4%, 4%, 1% and 0.4% respectively.

*(iii) Multilayer perceptron model (ANN) for verification of PF (Quarry C)*

To carry outthe MLP neural network analysis, ten parameters were selected which have been identified using PCA and SSE techniques. The identified parameters are Burden (B), Spacing (S), Charge column length (CCL), Stemming/ Burden ratio(T/B), Total amount of explosive (Qe), Chargeper delay (CPD), Distance (Di), Spacing/ Burden ratio (S/B), Volume of rock (Vr) and Scale distance (SD).

The network topology to predict the outcome (PF), consists of three layer (Input, hidden and output layer). In the input layer, there are ten input neurons, in the hidden layer, there are five neurons and one output neurons. The model summary indicated in Table 6.50, provides information related to the results of training and testing samples. Sum of square error is given for both training and testingsample. The small value (1.996) of the error related to training sample indicates the power of the model to predict the outcome. According to the Table 6.49, the Sum of squared errors(SSE) is 1.996 for training and 2.655 for testing samples.

**Table 6.49: Model Summary of PF using ANN (quarry C)**

| Model Summary for MLP | | |
|---|---|---|
| **Training** | Correlation value | 0.881 |
| | Sum of Squares Error | 1.996 |
| | Relative Error | .093 |
| | Stopping Rule Used | 1 consecutive step(s) with no decrease in error |
| | Training Time | 0:00:00.02 |
| **Testing** | Correlation value | 0.896 |
| | Sum of Squares Error | 2.655 |
| | Relative Error | .299 |

The graph between measured value of PF and predicted value by ANN technique has been plotted as shown in Figure 6.11. The value of coefficient of determination ($R^2$) was found tobe 0.896, which indicates the high degree of correlation of independent parameters with the PF.

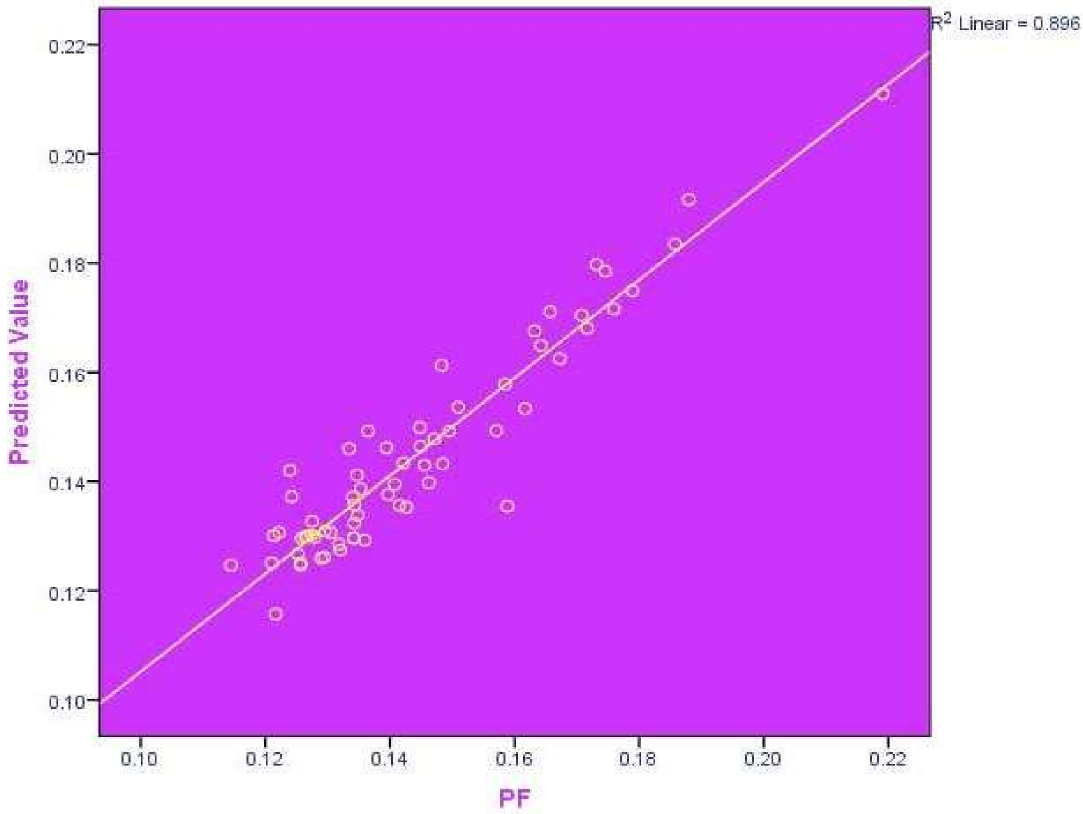


**Figure 6.11: Plot between measured and predicted value of PF by ANN technique (quarry C)**

The MLP neural network model also gives the information about the impact of each independent variable in terms of normalized importance. Figure 6.12 indicates the importanceof the variables. It is evident from the figure that in MLP technique, the most important parameter is scaled distance (SD) and inter hole delay (HD), which have influencing the PF with 100% and 83% extent respectively. Six parameters, namely, Vr (Volume of rock), charge per delay (CPD), stemming/burden ratio (T/B), column charge length (CCL). Total amount of explosive (Qe) and spacing (S) have an influence on PF with 60%, 40%, 38%, 35% 18% and 4% respectively.

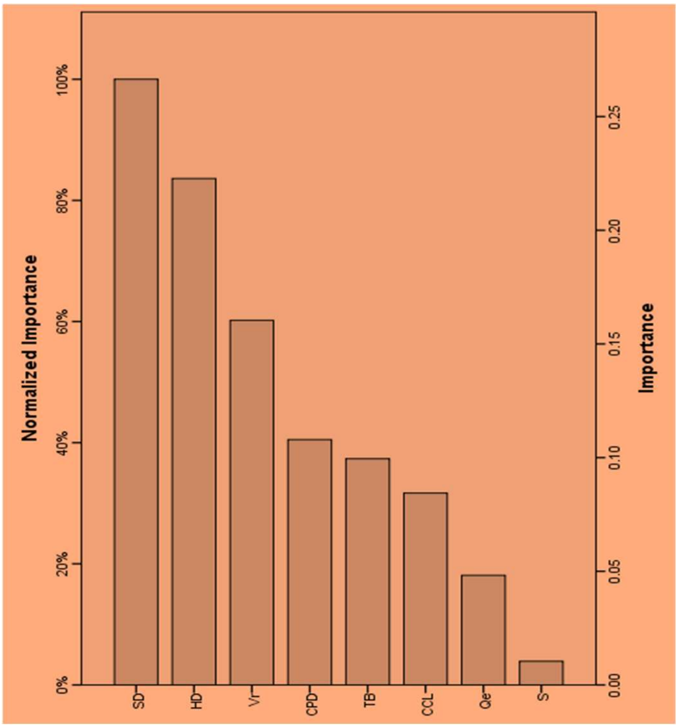


**Figure 6.12: Independent variables importance chart for PF (quarry C)**

## 6.6 Discussion

For quarry A, PCA has been identified six parameters namely, SD, S, Qe, CCL, PPV and Vr and SSE has been identified four parameters namely, T/B, Nh, Qe and Vr. The value of $R^2$ is 0.78 for PCA and 0.73 for SSE. It is clear that the PCA has high level of accuracy in comparison to SSE.

For quarry B, PCA has been identified 8 blasting design parameters namely, H, Di, S, Nr, T/CCL, Qe, D, Vr and SSE has been identified 7 blasting design parameters namely, S, T/B, CCL,Nr, Qe, CPD and Vr which affecting the PF. The value of $R^2$ for PCA and SSE are found to be 0.76 and 0.75 respectively.

For quarry C, PCA has been identified 8 blasting design parameters, namely, HD, T/B, SD, Vr, CPD, S, CCL and Qe and SSE has been identified 6 blasting design parameters, namely, B, S, CCL, Di, Qe and Vr, which have major impact on PF. The values of $R^2$ by PCA and SSE are found to be 0.86 and 0.81 respectively.

### 6.6.1 Identified blasting design parameters affecting PPV by PCA and SSE

PCA and SSE techniques have selected some blasting design parameters affecting powder factor and the coefficient obtained for the selected parameters are both positive and negative. The explanation of selected parameters is given below:

**(i) Total amount of explosive (Qe)-** The coefficient related to Qe is found positive by both PCA and SSE. Therefore, increase in the amount of explosive for blasting same volume of rock leads to increase in powder factor.

**(ii) Number of holes (Nh)-** The coefficient related to Nh is found positive by both PCA and SSE. However, this parameter may not be rationalized under the varying rock and blasting condition. Therefore, it needs further investigation.

**(iii) Column charge length (CCL)-** The coefficient related to CCL is found positive by both PCA and SSE. When CCL is increased, the amount of explosive per hole increases. It will lead to increase in total amount of explosive and subsequently leads to increase in powder factor.

**(iv) Stemming (T)-** The coefficient related to T is found positive by both PCA and SSE within the acceptable stemming range (0.75 – 1.3 times of burden).

**(v) Scaled distance (SD)-** The coefficient related to SD is found positive by both PCA and SSE. For a given SD, higher value of PF indicates better utilization of explosive, whereas, lower value of PF indicates poor utilization of explosive resulting in increased ground vibration levels.

**(vi) Spacing (S)** – The coefficient of spacing is negative in relation with PF. With increase in spacing the total volume of rock blasted also increases leading to decrease in PF.

**(vii) Volume of rock (Vr)-** The coefficient related to Vr is found negative by both PCA and SSE. Powder factor is calculated by amount of explosive required to break the rock of capacity 1 tonne. If the volume of rock fragmented due to blasting increases for amount of explosive remains same, then the powder factor will decrease.

**(viii) Stemming/Burden (T/B)-** The coefficient related to T/B has been found negative, which shows an inverse impact on PF. If the T/B ratio is inadequate, then the large amount of the gas energy will be transformed and wasted as ground vibration. Floyd (2012) also showed that the improper confinement of explosive resulted in 50 percent of explosive energy loss and results in poor powder factor.

**(ix) Peak particle velocity (PPV)-** The coefficient related to PPV has been found negative. Higher value of PF indicates better utilization of explosive, whereas, lower value of PF indicates poor utilization of explosive resulting in increased ground vibration levels.

## 6.7 Overview of results for PF

The results obtained for all the quarries using statistical (PCA and SSE) and ANN technique, in terms of blasting design parameters, $R^2$ and root means square error (RMSE), are summarized in Table 6.50.

**Table 6.50: Results at a glance for PF (Quarry A, B and C)**

| For prediction of PF | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Methods | Quarry A | | | Quarry B | | | Quarry C | | |
| | Equation developed by the statistical technique | $R^2$ value | RMSE | Equation developed by the statistical technique | $R^2$ value | RMSE | Equation developed by the statistical technique | $R^2$ value | RMSE |
| PCA | $PF = 0.394 - S \times (0.029) - Vr \times (0.000002970) + CCL \times (0.002) + SD \times (0.00005554) - PPV \times (0.001) - T \times (0.009) - RD \times (0.000008270)$ | 0.78 | 0.245 | $PF = 0.271 + D \times (0.001) - S \times (0.065) - Vr \times (0.000001691) - \frac{T}{CCL} \times (0.102) + Nr \times (0.015) + Di \times (0.00000278) + Qe \times (0.0000368) + H \times (0.010)$ | 0.77 | 0.358 | $PF = 0.210 - T/B \times (0.020) - Vr \times (0.000001312) + CCL \times (0.003) + SD \times (0.00005742) - S \times (0.023) - HD \times (0.001)$ | 0.86 | 0.754 |
| SSE | $PF = 0.203 + \frac{T}{B} \times (0.018) + Nh \times (0.001) + Qe \times (0.004) - Vr \times (0.00000373)$ | 0.73 | 0.354 | $PF = 0.378 + CCL \times (0.019) + \frac{T}{B} \times (0.011) + Qe \times (0.0000332)) + Nr \times (0.014) + CPD \times (0.001) - Vr \times (0.000007986) - S \times (0.064)$ | 0.75 | 0.465 | $PF = 0.187 - B \times (0.022) + S \times (0.002) + CCL \times (0.001) + Di \times (0.00000782) - Vr \times (0.000001486)$ | 0.81 | 0.886 |
| ANN | Parameters of PCA and SSE both | 0.94 | 0.258 | Parameters of PCA and SSE both | 0.96 | 0.280 | Parameters of PCA and SSE both | 0.90 | 0.158 |