Mathematical modelling of crushed rock dust concrete: Performance using compressive strength

V. Bhavana¹ and N. Venkata Sairam Kumar²

¹M. Tech Student, Department of Civil Engineering, R.V.R & J.C College of Engineering, Guntur-522019, Andhra Pradesh, India. bhavanavanga22@gmail.com
²Department of Civil Engineering, R.V.R & J.C College of Engineering, Guntur-522019, Andhra Pradesh, India. sairam852@gmail.com

ABSTRACT. The paper gives out a mathematical model developed using linear regression statistical method to envisage the 28-day strength of CRD concrete, considering M20, M30 and M40 grades concrete and CRD replacement percentages of 0%, 10%, 20%, 30% and 40% by weight of cement. Strength results of M40, M30 and M20 grades concrete are used to develop the relationship between CRD content and compressive strength. The ratios of compressive strengths between CRD and control concrete (CC) have been related to CRD replacement percentage. The expression, derived is with strength ratios and not with experimental strength values. The mathematical equation developed is independent of the specimen parameters and may be applicable to all types of specimens. The model is considered as it involves non-dimensional variables and is independent of the specimen size, water to binder ratio (w/b) and grade of concrete.

Keywords: Crushed rock dust, Compressive strength, Mathematical modelling, Green concrete, sustainable concrete.

1. INTRODUCTION

Concrete is an exceptional construction material is widely used in construction industry. Cement, being a key ingredient in concrete, consumes huge number of natural resources during the manufacturing process and is responsible for about 7% of all manmade CO₂ emissions. The use of non-pozzolanic/ pozzolanic fillers (marble dust, granite dust and lime stone powder), as supplementary cementitious materials, can reduce the cement consumption in concrete production and control CO₂ emissions from cement industry [1-2]. In an experimental study by Elayamany et al., it is revealed that, concrete produced with non-pozzolanic fillers has no negative effect on compressive strength compared to that of concrete with pozzolanic fillers. Moreover, concrete produced with non-pozzolanic fillers exhibited more resistance to segregation and bleeding than pozzolanic fillers. Marble dust, granite dust, crushed rock dust and lime stone powder commonly referred as quarry dust, is produced from stone processing industries and is an inert material, generally used for land filling, creating conservational problems [3, 4]. Quarry dust is chemically inactive, but can affect the properties of the concrete in a positive way. Enhancement in the behaviour of concrete with the use of non-pozzolanic fillers is almost identical when compared with pozzolanic fillers in long term. While the addition of non-pozzolanic/ pozzolanic fillers beyond certain limit leads to the reduction in strength when compared with cement concrete [5].

2. EXPERIMENTAL DETAILS

2.1. Materials

Fine aggregate of maximum size 4.75mm with zone III (IS 383:1970) [6] was used. Locally available crushed stone coarse aggregate of maximum size 20mm as per IS 383:1970 [6] was used. As per IS 12269: 1987 [7], OPC 53 grade cement was used. Its consistency and specific gravity are 32% and 3.1.
Fines of CRD with size less than 150µm is procured from the stone processing and crushing units and is shown in Fig. 1.

**Figure1.** Image showing the CRD at a local stone crushing unit

2.2. Concrete Mix design

Confirming to IS 10262: 2009 [8], M20, M30 and M40 concrete mixes are designed as CC mixes. Table 1 shows the concrete mix proportions.

2.3. Test Procedure

The concrete ingredients are mixed homogenously by using an electric pan mixer. The freshly mixed concrete is transferred into cube moulds of size 100 mm, in accordance to IS 516: 1959 [9] and then cured for 28 days. The concrete cube was kept uninterrupted for one day and then de-moulded, to extend for water curing for 28 days. The compressive strength is conducted on UTM, having a capacity of 100 Tonnes and the values are used for developing a mathematical model using linear regression statistical method to forecast the 28-day compressive strength of CRD concrete. XRD meter Rigaku Miniflex 600 is used for testing the CRD patterns.

| Mix designation | CRD (%) | CRD (kg/m³) | Cement (kg/m³) | Coarse aggregate (kg/m³) | Fine aggregate (kg/m³) |
|------------------|---------|-------------|----------------|--------------------------|-----------------------|
| C40              | 0       | 0           | 450            | 1309.5                   | 625.5                 |
| C41              | 10      | 45          | 405            | 1309.5                   | 625.5                 |
| C42              | 20      | 90          | 360            | 1309.5                   | 625.5                 |
| C43              | 30      | 135         | 315            | 1309.5                   | 625.5                 |
| C44              | 40      | 180         | 270            | 1309.5                   | 625.5                 |
| C30              | 0       | 0           | 410            | 1341.0                   | 652.0                 |
| C31              | 10      | 41          | 369            | 1341.0                   | 652.0                 |
| C32              | 20      | 82          | 328            | 1341.0                   | 652.0                 |
| C33              | 30      | 123         | 287            | 1341.0                   | 652.0                 |
| C34              | 40      | 164         | 246            | 1341.0                   | 652.0                 |
| C20              | 0       | 0           | 340            | 1355.58                  | 682.04                |
| C21              | 10      | 34          | 306            | 1355.58                  | 682.04                |
| C22              | 20      | 68          | 272            | 1355.58                  | 682.04                |
| C23              | 30      | 102         | 238            | 1355.58                  | 682.04                |
| C24              | 40      | 136         | 204            | 1355.58                  | 682.04                |
3. RESULTS AND DISCUSSION

3.1. XRD of crushed rock dust

The SEM photograph and XRD outline of CRD are shown in Fig. 2. The XRD outline of CRD shows a peak intensity between 20° and 30°, represents the existence of quartz (SiO₂). The composition of SiO₂ and Al₂O₃ in CRD is 84.46%. The SEM photograph of CRD exhibited the presence of irregular and angular particles. The percentages of NaAlO₂ and silicate in the CRD indicates the pozzolanic reactive nature. The sum of Al₂O₃, SiO₂ and Fe₂O₃ in CRD is 87.86% satisfies the requirement of 70%, as per ASTM C 618 [10]. Table 2 shows the chemical compositions of CRD.

![Figure 2. Image showing the XRD and SEM photograph of CRD](image)

| Compounds | Weight (%) |
|-----------|------------|
| P₂O₅      | 0.61       |
| TiO₂      | 0.26       |
| MnO       | 0.05       |
| K₂O       | 5.24       |
| Na₂O      | 2.46       |
| MgO       | 0.62       |
| CaO       | 3.16       |
| Fe₂O₃     | 3.40       |
| SiO₂      | 71.00      |
| Al₂O₃     | 13.46      |

3.2. Modelling of experimental data

The 28-days compressive strength ratios of CRD concrete (f_cr) and CC (f_cc) are given in Table 3. Since the same concrete with different CRD content is used for preparation of concrete testing specimens, the results are related to CRD replacement ratio and the compressive strength. The ratios of compressive strengths of the CRD concrete are identical and independent of grades of concrete. These ratios can be used to develop the generalized expression, which is free from the influence of grade of concrete and specimen parameters [11].

The relationship between the compressive strength ratios of CRD concrete and CRD content are shown in Fig. 3. Equation (1) represents the relation between the 28 days compressive strength ratio values of CRD and CC concrete and CRD content with an R² value of 0.8563. The compressive strength values of concrete obtained experimentally, computed by using equation (1) and the relative difference (%) between the computed and experimental compressive strength of CRD and CC concretes are shown in table 4.

Fig. 4 shows the relationship between the experimental and computed compressive strength of CRD and CC concretes. On the basis of regression analysis of compressive strengths of concrete, a statistical model is developed, which helps in predicting the strengths of CRD concrete over a range of
CRD replacement ratios and mix grades. This model, involving non-dimensional variables and is independent of specimen size and mix grade.

$$-0.0003(CRD)^2 + 0.0109(CRD) + 0.9988 = \frac{fc_{rd}}{fc_{cc}}$$  ----- (1)

Table 3. The 28-days compressive strength results of CRD concrete and CC with their corresponding ratios

| Mix Grade | Mix designation | CRD (%) | 150 mm cubes | 100 mm cubes |
|-----------|-----------------|---------|--------------|--------------|
|           |                 |         | $f_c$ (MPa)  | $f_{crd}/f_{cc}$ | $f_c$ (MPa) | $f_{crd}/f_{cc}$ |
| C20       | 0               | 29.43 ($f_c$) | 1.00 | 30.24 ($f_c$) | 1.00 |
| C21       | 10              | 31.76 | 1.08 | 31.14 | 1.03 |
| M20       | C22             | 20     | 32.58 | 1.11 | 33.25 | 1.10 |
|           | C23             | 30     | 29.33 | 1.00 | 31.74 | 1.05 |
|           | C24             | 40     | 27.21 | 0.92 | 28.55 | 0.94 |
| M30       | C30             | 0      | 41.62 ($f_c$) | 1.00 | 42.68 ($f_c$) | 1.00 |
|           | C31             | 10     | 45.77 | 1.10 | 47.25 | 1.11 |
|           | C32             | 20     | 46.54 | 1.12 | 48.19 | 1.13 |
|           | C33             | 30     | 42.41 | 1.02 | 44.21 | 1.04 |
|           | C34             | 40     | 37.48 | 0.90 | 41.46 | 0.97 |
| M40       | C40             | 0      | 50.23 ($f_c$) | 1.00 | 51.24 ($f_c$) | 1.00 |
|           | C41             | 10     | 52.67 | 1.05 | 54.12 | 1.06 |
|           | C42             | 20     | 54.41 | 1.08 | 56.38 | 1.10 |
|           | C43             | 30     | 53.22 | 1.06 | 54.65 | 1.07 |
|           | C44             | 40     | 48.44 | 0.96 | 49.52 | 0.97 |

Note: $f_c = $ Average compressive strength (MPa) of concrete cube specimens.  
$f_{cc} = $ Average strength of CC.  
$f_{crd} = $ Average compressive strength of CRD concrete.  
$f_{crd}/f_{cc} = $ Strength ratio between CRD concrete and CC
Figure 3. Relation between compressive strength ratio values of CRD/CC concretes and CRD content

Figure 4. Relation between experimental and computed compressive strength of concrete
### Table 4. Relative difference between compressive strength of concrete obtained experimentally and computed using equation (1)

| Mix grade | Mix designation | CRD (%) | Experimental ($f_c$) (MPa) | Computed ($f_c$) (MPa) | Relative difference (%) |
|------------|-----------------|---------|----------------------------|------------------------|-------------------------|
| M20 150 mm cubes | C20 | 0 | 29.43 | 29.39 | 0.12 |
| | C21 | 10 | 31.76 | 31.72 | 0.13 |
| | C22 | 20 | 32.58 | 32.28 | 0.92 |
| | C23 | 30 | 29.33 | 31.07 | -5.94 |
| | C24 | 40 | 27.21 | 28.10 | -3.27 |
| M30 150 mm cubes | C30 | 0 | 41.62 | 41.57 | 0.12 |
| | C31 | 10 | 45.77 | 44.86 | 1.99 |
| | C32 | 20 | 46.54 | 45.65 | 1.91 |
| | C33 | 30 | 42.41 | 43.94 | -3.61 |
| | C34 | 40 | 37.48 | 39.74 | -6.03 |
| M40 150 mm cubes | C40 | 0 | 50.23 | 50.17 | 0.12 |
| | C41 | 10 | 52.67 | 54.14 | -2.79 |
| | C42 | 20 | 54.41 | 55.09 | -1.25 |
| | C43 | 30 | 53.22 | 53.03 | 0.35 |
| | C44 | 40 | 48.44 | 47.96 | 0.99 |
| M20 100 mm cubes | C20 | 0 | 30.24 | 30.20 | 0.12 |
| | C21 | 10 | 31.14 | 32.59 | -4.66 |
| | C22 | 20 | 33.25 | 33.17 | 0.25 |
| | C23 | 30 | 31.74 | 31.93 | -0.59 |
| | C24 | 40 | 28.55 | 28.87 | -1.13 |
| M30 100 mm cubes | C30 | 0 | 42.68 | 42.63 | 0.12 |
| | C31 | 10 | 47.25 | 46.00 | 2.64 |
| | C32 | 20 | 48.19 | 46.81 | 2.86 |
| | C33 | 30 | 44.21 | 45.06 | -1.93 |
| | C34 | 40 | 41.46 | 40.75 | 1.71 |
| M40 100 mm cubes | C40 | 0 | 51.24 | 51.18 | 0.12 |
| | C41 | 10 | 54.12 | 55.23 | -2.04 |
| | C42 | 20 | 56.38 | 56.20 | 0.32 |
| | C43 | 30 | 54.65 | 54.10 | 1.01 |
| | C44 | 40 | 49.52 | 48.92 | 1.20 |

### 4. CONCLUSIONS

The following conclusions are made from the CRD concrete are,

1. The use of CRD with 0%, 10%, 20%, 30% and 40% as partial replacement for OPC cement in producing concrete.
2. The XRD results of CRD, it is noticed that between 20° and 30°, showed the existence of quartz (SiO₂).
3. From the experimental results, 20% CRD content in concrete showed enhanced results than CC.
4. The equation (1) developed using statistical modelling is independent of specimen size and shape and can be related to all types of specimens and mix grades.

REFERENCES

[1] Kumar NV, Ram KS. Sustainable use of waste crushed rock dust in concrete as partial replacement of cement. *Pollution Research*. 2018 Sep 37(3), pp. 684-689.
[2] Kumar NV. Crushed rock dust as filler material in concrete. *Materials Today: Proceedings*. 2021 Jan 1; 43:1714-9.
[3] Kumar NV. Crushed rock dust as filler material in concrete. *Materials Today: Proceedings*. 2021 Jan 1; 43:1714-9.
[4] Kumar NV. Flexural strength of crushed rock dust concrete at elevated temperatures. In *IOP Conference Series: Materials Science and Engineering* 2020 Dec 1 (Vol. 988, No. 1, p. 012016). IOP Publishing.
[5] Kumar NV, Ram KS. Performance of concrete at elevated temperatures made with crushed rock dust as filler material. *Materials Today: Proceedings*. 2019 Jan 1; 18:2270-8.
[6] IS: 383-1970. Specifications for coarse and fine aggregates from natural resources for concrete, New Delhi, India: Bureau of Indian standards.
[7] IS: 12269-1987. Specification for 53 grade ordinary Portland cement, New Delhi, India: Bureau of Indian Standards.
[8] IS: 10262-2009. Recommended guidelines for concrete mix design, New Delhi, India: Bureau of Indian Standards.
[9] IS: 516: 1959 Methods of test for strength of concrete. New Delhi, India: Bureau of Indian Standards.
[10] ASTM C 618. (2019). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for use in Concrete. *ASTM International*, PA, USA.
[11] Bhanja S, Sengupta B. Investigations on the compressive strength of silica fume concrete using statistical methods. *Cement and Concrete Research*. 2002 Sep 1; 32(9):1391-4.