# Modelling of Mixtures Using Taguchi Method to Identify Properties of Self-Curing High Strength Concrete

**Nagesh T. Suryawanshi[1] and Sunil B. Takare[2]**

**Abstract :** The conventional curing methods were found superficial and hence ineffective in case of high strength concrete. Super absorbent polymers are the new materials which could be effective for the internal curing of High Strength Concrete mixes (HSC). However, the self-curing of HSC produced using high reactive metakaolin has not yet been examined adequately. Hence, the purpose of this study is to investigate the mechanical properties of Metakaolin based high strength concrete in combination with Super Absorbent Polymer (SAP). In this study, the Taguchi experiment method is used to achieve the best possible combination of factors. The design of the experiment was prepared by determining control factors. The specimens like cubes, cylinders and beams were cast considering all combinations and cured under different curing conditions for a period of 28 days. Specimens were tested under the universal testing machine and the results obtained showed about 50-55% increase in compressive strength of the self-curing mix than the conventional non self-curing mix. The obtained strength of the self-curing concrete nearly equals the strength of moist-cured concrete. Hence, the study suggests that the Taguchi technique is the most appropriate method of mix optimisation and it certainly reduces the time and cost of experimentation. The multi-regression analysis also proposes equations which offer predicted values of all the mechanical properties. These values strongly correlate with the values found experimentally.

*Keywords:* *High Reactive Metakaolin; Super Absorbent Polymers; Universal Testing Machine; Taguchi Method.*

## INTRODUCTION

To produce high strength concrete, Supplementary Cementitious Materials (SCMs) are added to concrete mixtures. The addition of SCMs in a higher quantity may increase the curing time. In such concrete, water supplied internally is more effective than external curing. According to the Janson Weisss (2012) stated that internal curing is the process of supplying water internally in concrete to support the hydration process and reduce the water loss. The study conducted by Castro et al. (2010) reveals that concrete produced of low water to cement ratios is likely to reduce strength due to insufficient water for the hydration process. The study shows that the external curing of higher grade concrete is ineffective due to its impermeable nature; only curing found is superficial. Internal curing allows water to distribute uniformly throughout the concrete matrix Super absorbent polymers are non- toxic, water soluble and having high water absorption capacity , Hence, these polymers were used as internal curing agents in concrete of higher grade. Based on this concept, Islam (2011) conducted an experiment by using lightweight aggregates as an internal curing agent. Kong et al. (2015) investigated the influence of pre-soaked Super Absorbent Polymer (SAP) on the properties of high strength concrete. They observed that pre-soaked SAPs reduced the compressive strength of high strength concrete in initial days. The enhancement in hydration process was noticed partially in later days but due to macro voids left by SAP, it leads to reduction in strength. Thong et al. (2015) discussed physical properties of polyvinyl

[1]Assistant Professor in Civil Engineering, R.I.T. Rajaramnagar, Islampur, Maharashtra, India.
[2]Principal, ABMSPs APCOE & R Pune, Maharashtra, India.
Email: nagesh.suryawanshi@ritindia.edu

alcohol (PVA) and its effect on engineering properties of cement based composite material. It was produced about 90 years ago and used for various applications. The use of PVA in the construction sector was not muchpopular. Hence, the need for further research also addressed, Kim et al. (1998) evaluated the properties and internal structure of mortars and concrete produced by addition of PVA up to 2%. The result was also compared with mortar and concrete produced without PVA. It was found that addition of PVA in mortars and concrete increased air voids, fluidity and reduced bleeding. According to Trtik et al. (2010), SAP is more effective in high performance concrete with low water ratios. A SAP added in the dry state, absorbs water and releases it after setting it which helps in reducing autogenous shrinkage. After the setting process, water can travel only limited distance, hence SAP must disperse well and release water at appropriate time. Lee et al. (2010) explored self-sealing of cracks in cement based materials by using super absorbent polymers. SAP absorbs about 20 mg of water and slightly swells. When the concrete hardens, the SAP releases water slowly, and then it collapses. Hasholt et al. (2012) examined the water absorption of SAP and influence of excess water in high strength mixes. It was also noticed that over estimation of SAP absorption reduced compressive strength as well as tensile strength. Olawuyi et al. (2017) observed that absorption and desorption during the hydration process left large voids and it would negatively affect mechanical properties of high performance concrete. The most influencing factors found were SAP content, sizes, binder composition, and curing age. Yildizel et al. (2020) studied the combined utilization of Taguchi and Extreme Vertices Design Techniques to optimize concrete mixtures. Ikeagwuani et al. (2020) studied optimization of eco-friendly high strength concrete using the Taguchi method. Warda et al. (2020) studied high strength concrete to find the best sustainable mix proportions using the Taguchi method. The authors concluded that multi- response optimizations were required to get the best mix proportions.

It is found from the literature reviewed that self-curing of high strength concrete by using super absorbent polymers is an effective method. It is also found that to achieve the desired properties, it is essential to add the right percentage and right quality of polymers. The literature available about mixture proportioning of self-curing concrete was found to be inadequate. Hence this study aims to estimate the proper mixture proportioning of all ingredients including SAP percentage which is very important to achieve better properties in high strength concrete. Hence this research strives to optimize all the ingredients of high strength concrete using the Taguchi method in order to maximize its strength.

## Taguchi Method

The Taguchi method has been generally used to optimize the constituents of mix design. It is a systematic approach by which the testing time and the experimental cost can significantly reduce (Chouet et al. 2010). According to Taguchi, performance of any product depends on its environmental conditions and components used to produce it. It is therefore necessary to consider these two conditions while determining optimum working conditions (Turkmen et al. 2010).The primary concept in the Taguchi method is "noise factors". It is used to indicate the variability in performance, which may be the reason of product failure. A noise factor is anything that causes deviation of characteristics from the target values decided. The main objective is to maximize the strength parameters. In the present study, four variables with four levels are used which results in 16 combinations of each mix. L16 Orthogonal Array (OA) is arranged for each mix in this study. Four parameters were selected for the mix, viz. Cement (kg/m3), the percentage of High Reactive Metakaolin (HRM) (kg/m3), Poly Vinyl Alcohol (PVA) (kg/m3), and Poly Acrylic Acid (PAA) (kg/m3). Using the Taguchi experimental design and multi-regression analysis, a statistical investigation of the experimental data obtained through Minitab18.0 was carried out. For analysis, the taguchi approach and multi-regression analysis sixteen combinations are presented with four replicates by each run.

## Materials and Methods

### *Materials*

The ordinary Portland cement of 53 grades which conforms to IS 12269 –1987 was used for making concrete. The physical properties of cement like fineness, setting time, and soundness etc. were examined in the laboratory. The chemical and physical properties of highly reactive Meta kaolin HRM were confirmed from IS 1489 Part 2 (1991).The chemical composition of cement and Metakaolin is given in *Table 1.*

*Aggregates*

The locally available natural sand from the Nira river was used for the experimentation. The properties of sand like specific gravity, fineness modulus, water absorption etc. were identified as per the standard procedures (IS 383:1970). The coarse aggregates used were crushed stone metals of basaltic nature. Various properties such as surface texture, shape, aggregate size, fineness modulus, specific gravity, and water absorption were checked by following the standard procedures (IS 2386:1963). Both fine and coarse aggregates conformed to the requirements as per IS. The physical properties of fine and coarse aggregates are shown in *Table 2.*

*Super Absorbent Polymers (SAPs)*

Povinyl alcohol (PVA) is produced commercially from polyvinyl acetate, usually by a continuous process. It is a compound of poly ethylene glycol and is water soluble in nature. The Poly acrylic acid (PAA) is one of the most commonly used viscosity-enhancing agents with a significant effect on resisting bleeding and segregation. PVA and PAA absorb water about 130 and 300 times of its weight respectively. A swollen view of PVA and PAA is shown in *Figure 1.*

EDS is the energy dispersive X-ray analysis technique used for elemental analysis; it shows chemical composition with atomic weight percentage. *Figures 2 and 3* show the EDS test images of SAPs namely PVA and PAA and *Table 3* shows the elemental composition of both SAPs in percentages. The elemental composition shows that higher percentages of atoms of CaCO3 and SiO2 are present in both SAPs. It would contribute in water retention, hydration and strength development process. The atoms present in both SAPs are hydrophilic in nature hence absorb and retain more water. This indicates the water retention ability of both SAPs.

*Super Plasticizer*

Super plasticizers, also known as high range water reducers, are of great help today in the production of high strength concrete. The super plasticizer used was a high range water reducer of sulphonate naphthalene formaldehyde type. The specific gravity as per the manufacturer's specification is about 1.20.

**Table 1: Chemical Composition of Ordinary Portland Cement and Metakaolin**

| Sr. No. | Parameters (in %) | OPC | Metakaolin |
|---|---|---|---|
| 1 | $SiO_2$ | 19.60 | 52.8 |
| 2 | CaO | 60.80 | <0.1 |
| 3 | $Fe_2O_3$ | 6.10 | 4.21 |
| 4 | $Al_2O_3$ | 4.15 | 36.3 |
| 5 | ($SO_3$) | 2.40 | - |
| 6 | (MgO) | 1.50 | 0.81 |
| 7 | loss on ignition | 3.42 | 3.53 |
| 8 | $K_2O$ | 0.03 | 0.53 |

**Table 2: Physical Properties of Aggregates**

| Sr. No. | Property | Fine Aggregates | Coarse Aggregates |
|---|---|---|---|
| 1 | Fineness Modulus | 3.12 | 4.85 |
| 2 | Specific Gravity | 2.61 | 2.65 |
| 3 | Water Absorption | 0.5 | 0.6 |

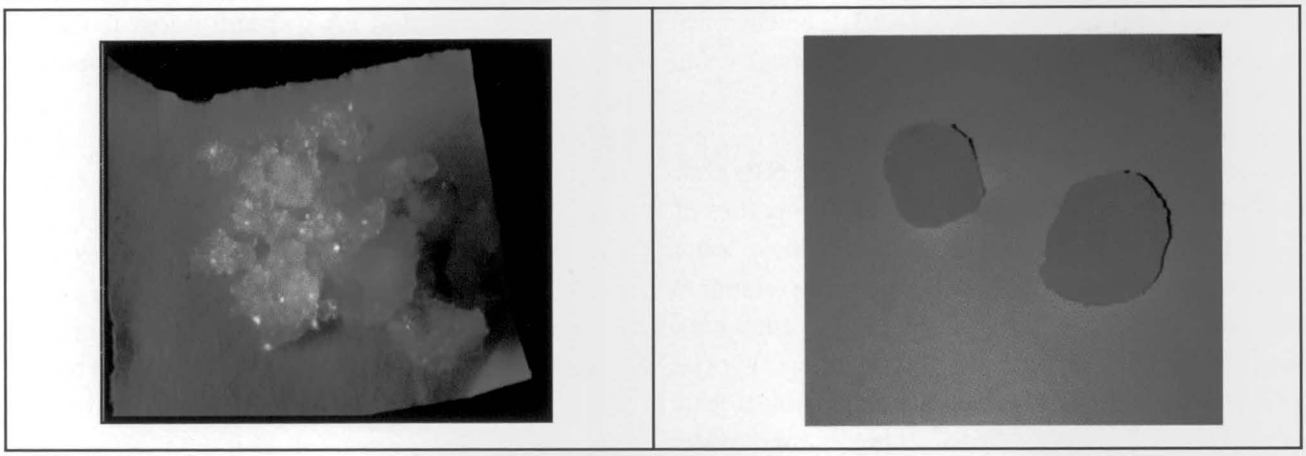


**Figure 1: Swollen State of PVA and PA**

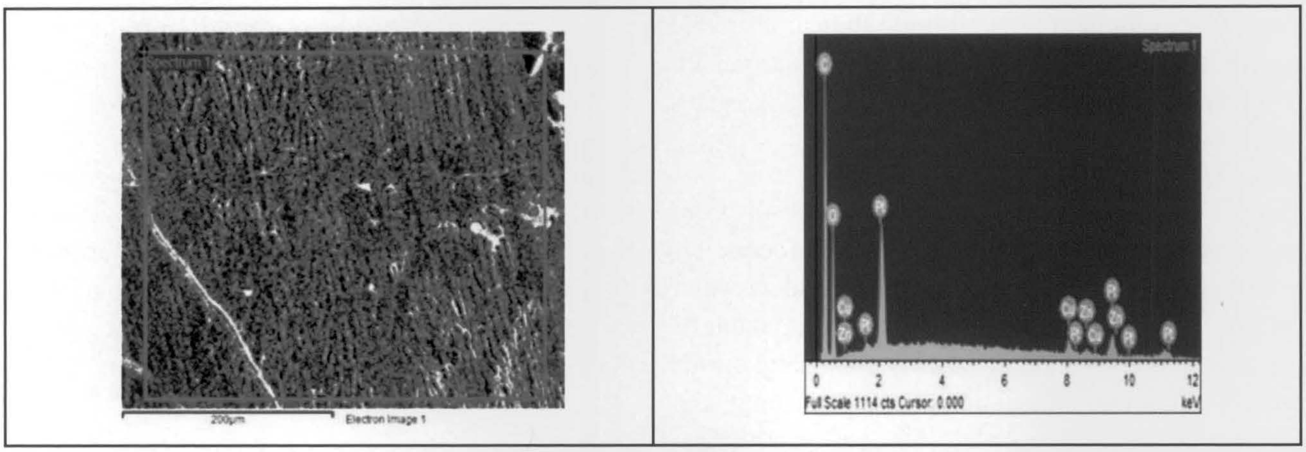



**Figure 2: EDS Test on Polyvinyl Alcohol**

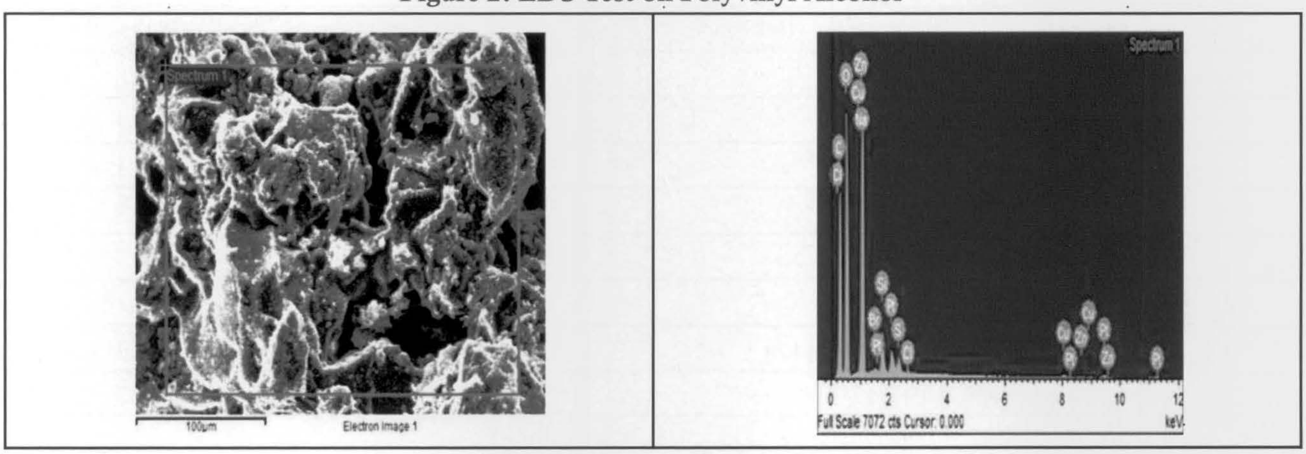



**Figure 3: EDS Test on PAA**

**Table 3: Elemental Composition**

| Elements | PVA (%) | PAA (%) |
|---|---|---|
| CaCO3 | 67.42 | 52.63 |
| SiO2 | 31.87 | 41.11 |
| FeS2 | - | 0.16 |
| KCL | - | 0.02 |
| Cu | 0.46 | 0.08 |
| Zn | 0.25 | 0.04 |

## METHODOLOGY

### Mixture Design

As per the I.S. 10262-2009, the experimental program was designed to produce a high strength concrete mix of M60 grade by addition of highly reactive Meta kaolin (HRM). The target mean strength found was 68.25 N/mm2. A control mix was designed as low water cement ratios vary from 0.32 to 0.42. High reactive metakaolin incorporated with OPC was added (10% by the weight of cement) to obtain the desirable strength. (Suryawanshi, 2018; Kim, 2007; Wild et al., 1996). A dose of super absorbent polymers up to 1 % by the weight of cement was tried in low W/C. It was found that a higher percentage of SAPs resulted in the decrease in strength parameters. (EI –Dieb et al. 2011). Hence, as a first step, PVA was used solely with a dosage of 0.02 % by the weight of cement. Then PVA was used in combination with PAA. The specimens were cast by using a lower percentage of SAPs in combination only 0.02% by the weight of cement (PVA + PAA).Different weight ratios of both SAPs were tried. Hence, the program designed based on the Taguchi approach to evaluate self- curing possibilities of high strength concrete using super absorbent polymers. Figure 4 shows a flow chart of the methodology adopted to conduct the experimental work.

### Taguchi Approach

The Taguchi method used to design the experiment using the software Minitab 18. The control factors determined were ordinary Portland cement, Metakaolin, PVA and PAA. *Table 4* shows the input parameters and their levels. The various mix proportions arrived at by the Taguchi orthogonal array are shown in *Table 5*. *Table 6* shows the mixture proportions of 16 combinations designated by SC (Self –cured). The Taguchi analysis was also used to determine the optimum mixture which produces maximum strength. In this method, the response index calculated for each factor is based on signal to noise ratio principle. It means a higher signal to noise ratio (S/N ratio) provides a better response index.

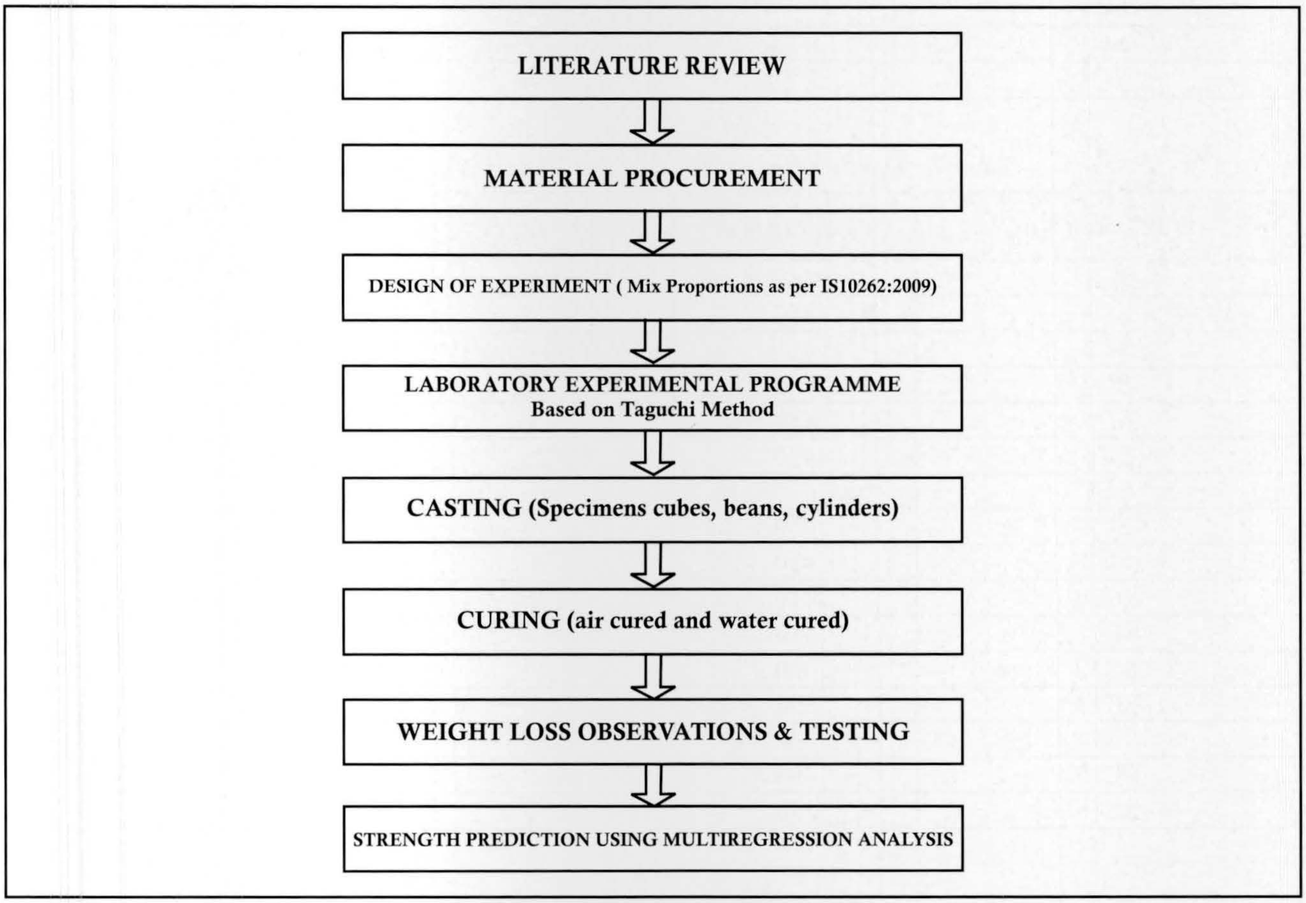



**Figure 4: Flow Chart of Methodology**

**Table 4: Input Parameters with their Levels**

| Control Factor | L1 | L2 | L3 | L4 |
|---|---|---|---|---|
| A: Cement ($Kg/m^3$) | 450 | 430 | 410 | 390 |
| B: HRM ($Kg/m^3$) | 22.5 [5%] | 32.25[7.5%] | 41[10%] | 48.75[12.5%] |
| C: PVA($Kg/m^3$) | 0.0225[25%] | 0.0258[30%] | 0.0287[35%] | 0.0312[40%] |
| D: PAA($Kg/m^3$) | 0.0675[75%] | 0.0602[70%] | 0.0533[65%] | 0.0468[60%] |

**Table 5: Taguchi $OA_{16}$ [$4^4$] Orthogonal Array**

| Trial batch No. | Factor A | Factor B | Factor C | Factor D |
|---|---|---|---|---|
| SC1 | 1 | 1 | 1 | 1 |
| SC2 | 1 | 2 | 2 | 2 |
| SC3 | 1 | 3 | 3 | 3 |
| SC4 | 1 | 4 | 4 | 4 |
| SC5 | 2 | 1 | 2 | 3 |
| SC6 | 2 | 2 | 1 | 4 |
| SC7 | 2 | 3 | 4 | 1 |
| SC8 | 2 | 4 | 3 | 2 |
| SC9 | 3 | 1 | 3 | 4 |
| SC10 | 3 | 2 | 4 | 3 |
| SC11 | 3 | 3 | 1 | 2 |
| SC12 | 3 | 4 | 2 | 1 |
| SC13 | 4 | 1 | 4 | 2 |
| SC14 | 4 | 2 | 3 | 1 |
| SC15 | 4 | 3 | 2 | 4 |
| SC16 | 4 | 4 | 1 | 3 |

**Table 6: Mixture Proportions of the 16 Series of the Specimens**

| Trial batch No. | Cement ($Kg/m^3$) | HRM ($Kg/m^3$) | PVA ($Kg/m^3$) | PAA ($Kg/m^3$) |
|---|---|---|---|---|
| SC1 | 450 | 22.5 | 0.0225 | 0.0675 |
| SC2 | 450 | 32.25 | 0.0258 | 0.0602 |
| SC3 | 450 | 41 | 0.0287 | 0.0533 |
| SC4 | 450 | 48.75 | 0.0312 | 0.0468 |
| SC5 | 430 | 22.5 | 0.0258 | 0.0533 |
| SC6 | 430 | 32.25 | 0.0225 | 0.0468 |
| SC7 | 430 | 41 | 0.0312 | 0.0675 |
| SC8 | 430 | 48.75 | 0.0287 | 0.0602 |
| SC9 | 410 | 22.5 | 0.0287 | 0.0468 |
| SC10 | 410 | 32.25 | 0.0312 | 0.0533 |
| SC11 | 410 | 41 | 0.0225 | 0.0602 |
| SC12 | 410 | 48.75 | 0.0258 | 0.0675 |
| SC13 | 390 | 22.5 | 0.0312 | 0.0602 |
| SC14 | 390 | 32.25 | 0.0287 | 0.0675 |
| SC15 | 390 | 41 | 0.0258 | 0.0468 |
| SC16 | 390 | 48.75 | 0.0225 | 0.0533 |

**Table 7: Specimens Size and Casting Details**

| Type | Size (mm) | No. of Specimen | No. of Batches |
|---|---|---|---|
| Cube | 150 x150 x 150 | 27 | 16 |
| Cylinder | 150 x 300 | 27 | 16 |
| Beam | 150 x 150 x 700 | 27 | 16 |

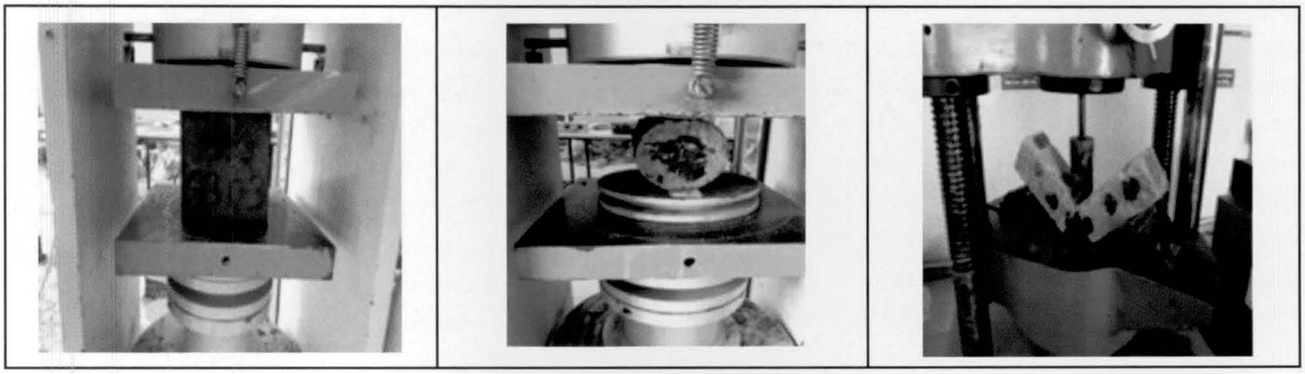


**Figure 5: Testing of Specimens**

**Figure 6: Homogeneous Mixes with True Slump**

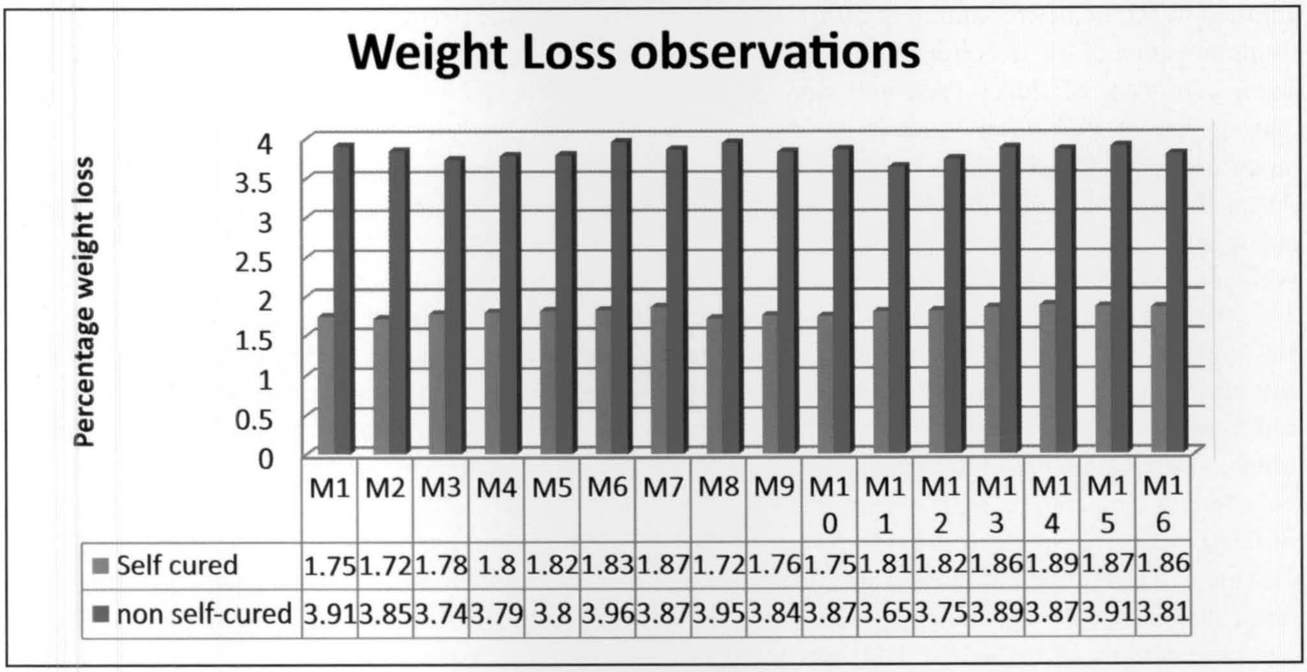



**Figure 7: Percentage Weight Loss of Self-Cured and Non-Cured Mixes (days)**

### Tests of Fresh and Hardened Concrete

The slump cone test was conducted to measure the workability; the slump values were maintained between 50 and 100 mm for all mixtures by addition of the required dose of super plasticizer.

The specimens like cube, cylinder and beams were cast and every day weight loss observations were made to check the water retention ability, thereby self-curing possibilities. The size and casting details of the specimens are shown in *Table 7*. The specimens cast were cured in different curing conditions such as self-curing, non-curing and moist curing for a period 28 days. After curing, the cubes and cylinders were tested under the compression testing machine of 300T and the beams were tested under the universal testing machine of 60T. *Figure 5* shows the testing of specimens. A multiple nonlinear regression analysis was used to develop a statistical model to predict the strength and to show the relationship between the predicted and observed values.

## RESULTS AND DISCUSSION

### Effect on Workability

HRM is a pozzolanaic material. When added with OPC, it increases the water demand. The addition of water soluble super absorbent polymers forms a gelatinous solution and the resultant mix was sticky. This is because of its ability of absorption and retention of water. The dose of super plasticizer was adjusted to get the desired slump of 50-100 mm. The slump obtained of all 16 combinations was the True slump. The dose of PVA+ PAA was more effective than the use of PVA alone in retaining water in the mixes comprising high reactive metakaolin. Figure 6 shows the homogeneously mixed concrete and the obtained True slump of the sample mixes.

### Weight Loss Observations (Water Retention)

Self –cured specimens are the cubes casted using SAPs and non self-cured specimens are the cubes casted without adding SAPs. Both self-cured and non self-cured specimens were kept for air dry curing at room temperature in a laboratory environment. Due to the surrounding temperature, both specimens lost water, which resulted in a decrease in the weight of specimens. During the entire experiment, weight of each cube was noted every day for 28 days. The weight loss observations of self-cured and non self-cured specimens on 7, 21, and 28 days were measured for all the sixteen different combinations. Figure 7 shows the percentage weight loss with time of self-cured and non self-cured mixes. It was seen that the conventional non self-cured mixes lost more water than the all self-cured mixes. Self-cured concrete shows a lower weight loss which means a better water retention. The maximum weight loss observed was 3.81 % in non-self-cured mixes and 1.86 % for self-cured mixes. It means almost double weight loss was observed in non self-cured mixes as compared to self-cured mixes. This indicates a better water retention ability of self-cured mixes than non self-cured mixes. It was also observed that the use of higher weight ratio of SAP and higher percentage of Matakaolin would result in a stiff mix.

### Effect on Hardened Concrete Property

#### *Test Results of Compressive Strength*

A test of compressive strength was conducted on the specimens of three regime conditions, namely self-cured, Non self-cured and moist cured at the end of 28 days. At 28 days of curing period, the maximum average compressive strength obtained was 46.8 N/mm2 for non self-cured mix and 70.2 N/mm2 for self-cured mix; it indicates that the strength obtained of self-cured mix is 1.5 times more than the strength of Non self-cured mix. It is important to note that the strength obtained of self-cured concrete nearly equals the strength obtained of moist cured concrete. As per the Taguchi approach, the larger is the better; mix- 1 gives a higher strength equal to 70.2 N/mm2, which is more than the target strength (68.25 N/mm2). As the main objective was to optimize the mix, the results obtained show that mix -5 is the optimum mix as its strength nearly equals the target strength. Figure 8 clearly shows that there was a decline in strength from mix 6 onwards.

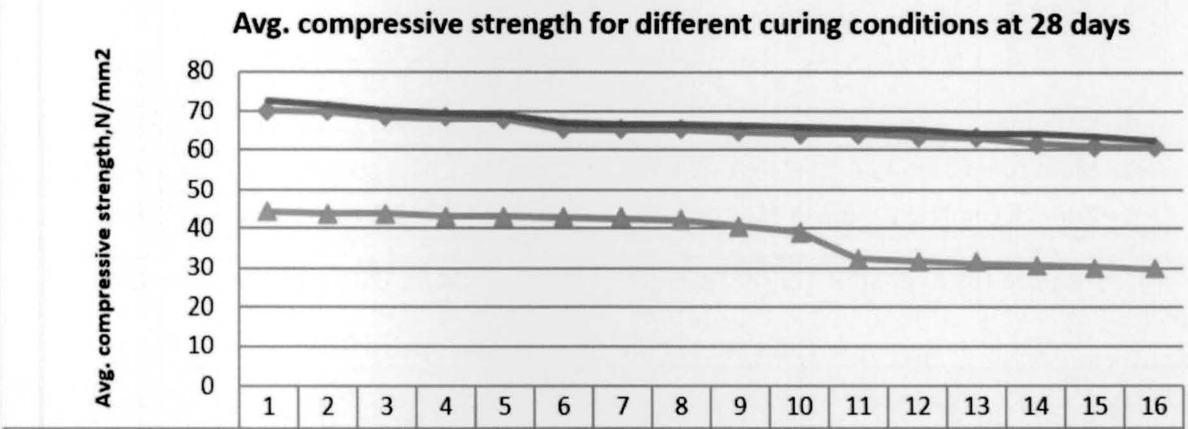
#### *Test Results of Flexural Strength*

The flexural strength of self-cured mixtures was determined at the age of 28 days. Beam specimens were cured under different curing conditions, same as done in the compression test. At 28 days of curing period, the maximum average flexural strength obtained was 3.54 N/mm2 and 5.95 N/mm2 for non-cured mix and self-cured mix respectively. It indicates that the strength obtained of the self-cured mix is 1.7 times more than the strength of non-cured mix. Figure 9 shows the average flexural strength obtained under different curing conditions.

***Test Results of Split Tensile Strength***

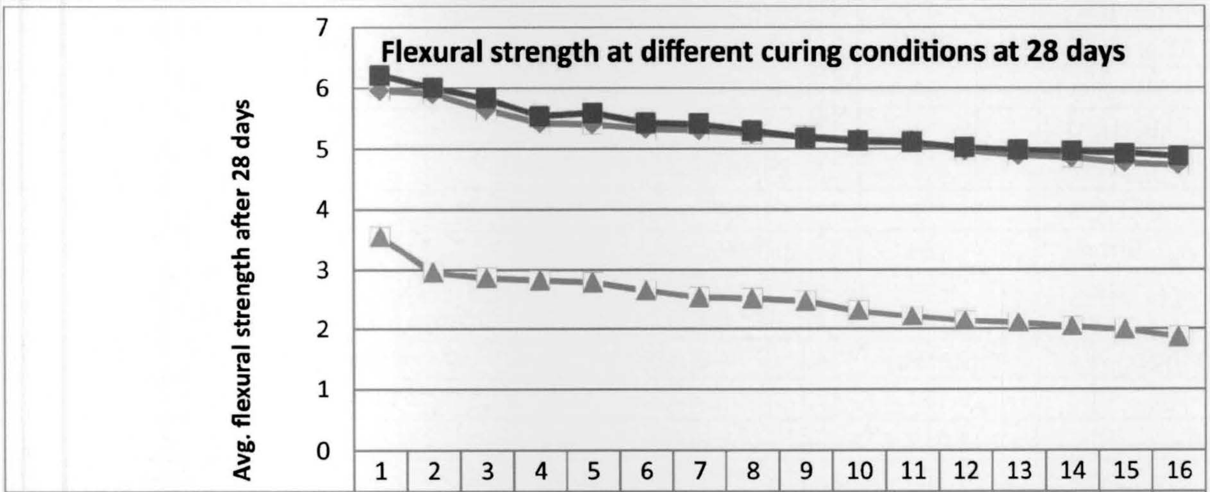
The split tensile (Indirect tensile) strength of self-cured mixtures was determined at the age of 28 days. Cylinder specimens were cured under different curing conditions. At 28 days of curing period, the average split tensile strength obtained was 3.21 N/mm2 (Max.) for non self-cured mix and 5.1 N/mm2 (Max.) for self-cured mix. It indicates that the strength obtained of self-cured mix is 1.6 times more than the strength of non-cured mix. Figure 10 depicts the average split tensile strength obtained under different curing conditions.

As expected, by increasing the compressive strength, the flexural and split tensile strengths increased. It showed a strong relationship in the mechanical properties.



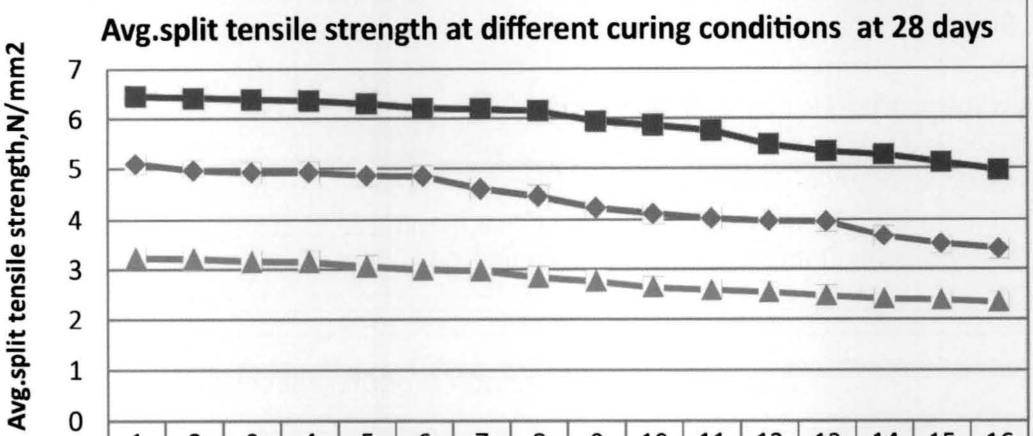

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Self curing | 70.2 | 69.85 | 68.32 | 68.21 | 68.1 | 65.4 | 65.2 | 65.2 | 64.6 | 64.2 | 64.2 | 63.4 | 63.1 | 61.9 | 61.2 | 60.8 |
| Moist curing | 72.54 | 71.4 | 70.32 | 69.32 | 69.12 | 66.86 | 66.8 | 66.5 | 66.4 | 65.8 | 65.7 | 65.3 | 64.3 | 64.3 | 63.5 | 62.4 |
| Non self curing | 44.1 | 43.9 | 43.8 | 43.2 | 43.1 | 42.8 | 42.5 | 42.1 | 40.75 | 39.4 | 32.6 | 31.8 | 31.2 | 30.8 | 30.4 | 29.82 |

**Figure 8: Avg. Compressive Strength at 28 Days Under Different Curing Regime**




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| At 28 days Self curing | 5.95 | 5.9 | 5.63 | 5.42 | 5.4 | 5.32 | 5.3 | 5.25 | 5.2 | 5.15 | 5.12 | 4.96 | 4.89 | 4.85 | 4.76 | 4.72 |
| At 28 days Moist curing | 6.21 | 6 | 5.82 | 5.53 | 5.58 | 5.42 | 5.4 | 5.29 | 5.18 | 5.12 | 5.1 | 5.02 | 4.98 | 4.95 | 4.92 | 4.87 |
| At 28 days Non self curing | 3.54 | 2.95 | 2.86 | 2.82 | 2.79 | 2.65 | 2.54 | 2.52 | 2.48 | 2.31 | 2.22 | 2.14 | 2.1 | 2.04 | 1.98 | 1.86 |

**Figure 9: Avg. Flexural Strength at 28 Days Under Different Curing Regime**




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Self curing | 5.1 | 4.96 | 4.92 | 4.92 | 4.86 | 4.84 | 4.6 | 4.45 | 4.23 | 4.12 | 4.02 | 3.97 | 3.96 | 3.65 | 3.5 | 3.4 |
| Moist curing | 6.45 | 6.42 | 6.39 | 6.36 | 6.3 | 6.21 | 6.19 | 6.15 | 5.94 | 5.86 | 5.76 | 5.48 | 5.34 | 5.27 | 5.12 | 4.96 |
| Non self curing | 3.21 | 3.2 | 3.15 | 3.14 | 3.05 | 2.99 | 2.97 | 2.84 | 2.76 | 2.64 | 2.59 | 2.54 | 2.47 | 2.41 | 2.39 | 2.34 |

**Figure 10: Avg. Split Tensile Strength at 28 Days Under Different Curing Regime**

**Table 8: Response Table for S/N Ratio for Compressive Strength at 28 Days**

| Level | A:Cement | B:HRM | C:PVA | D:PAA |
|---|---|---|---|---|
| 1 | 36.79 | 36.45 | 36.27 | 36.27 |
| 2 | 36.39 | 36.29 | 36.33 | 36.33 |
| 3 | 36.14 | 36.22 | 36.25 | 36.30 |
| 4 | 35.81 | 36.17 | 36.28 | 36.23 |
| Delta | 0.98 | 0.28 | 0.08 | 0.10 |
| Rank | 1 | 2 | 4 | 3 |

**Table 9: Analysis of Variance**

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Regression | 4 | 62.6885 | 15.6721 | 218.62 | 0.000 |
| A:Cement | 1 | 58.7731 | 58.7731 | 819.87 | 0.000 |
| B:HRM | 1 | 3.8150 | 3.8150 | 53.22 | 0.000 |
| C:PVA | 1 | 0.0567 | 0.0567 | 0.79 | 0.393 |
| D:PAA | 1 | 0.0437 | 0.0437 | 0.61 | 0.451 |
| Error | 11 | 0.7885 | 0.0717 | | |

**Table 10: Response Table for S/N Ratio for Flexural Strength at 28 Days**

| Level | A:Cement | B:HRM | C:PVA | D:PAA |
|---|---|---|---|---|
| 1 | 15.15 | 14.58 | 13.97 | 14.43 |
| 2 | 14.51 | 14.50 | 14.14 | 14.47 |
| 3 | 14.16 | 14.06 | 14.39 | 13.90 |
| 4 | 12.99 | 13.67 | 14.32 | 14.02 |
| Delta | 2.16 | 0.91 | 0.42 | 0.57 |
| Rank | 1 | 2 | 4 | 3 |

**Table 11: Analysis of Variance**

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Regression | 4 | 3.96165 | 0.99041 | 33.09 | 0.000 |
| A:Cement | 1 | 3.07720 | 3.07720 | 102.81 | 0.000 |
| B:HRM | 1 | 0.62128 | 0.62128 | 20.76 | 0.001 |
| C:PVA | 1 | 0.06216 | 0.06216 | 2.08 | 0.177 |
| D:PAA | 1 | 0.20100 | 0.20100 | 6.72 | 0.025 |
| Error | 11 | 0.32925 | 0.02993 | | |
| Total | 15 | 4.29089 | | | |

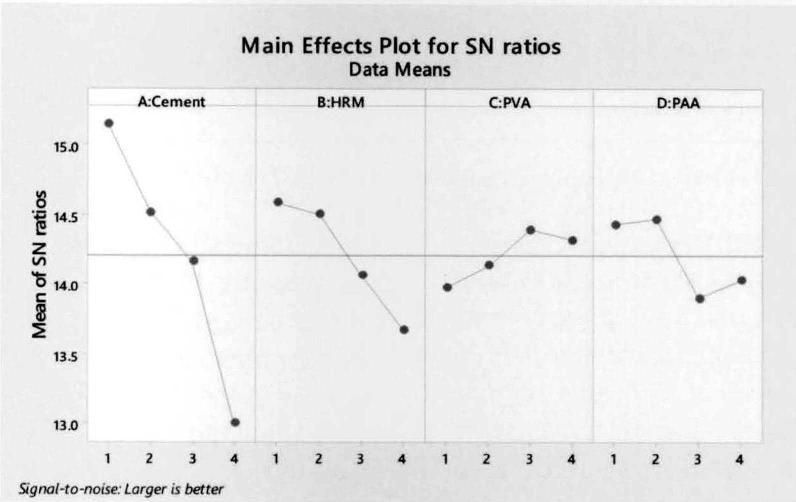



**Figure 12: Effect of Input Parameters on Flexural Strength at 28 Days**

**Table 12: Response Table for S/N Ratio for Split Tensile Strength at 28 days**

| Level | A:Cement | B:HRM | C:PVA | D:PAA |
|---|---|---|---|---|
| 1 | 13.93 | 13.09 | 12.64 | 12.66 |
| 2 | 13.41 | 12.79 | 12.62 | 12.73 |
| 3 | 12.22 | 12.52 | 12.64 | 12.62 |
| 4 | 11.18 | 12.35 | 12.84 | 12.74 |
| Delta | 2.76 | 0.74 | 0.21 | 0.11 |
| Rank | 1 | 2 | 3 | 4 |

Table 13: Analysis of Variance

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Regression | 4 | 4.60641 | 1.15160 | 91.95 | 0.000 |
| A:Cement | 1 | 4.31520 | 4.31520 | 344.55 | 0.000 |
| B:HRM | 1 | 0.28322 | 0.28322 | 22.61 | 0.001 |
| C:PVA | 1 | 0.00578 | 0.00578 | 0.46 | 0.511 |
| D:PAA | 1 | 0.00221 | 0.00221 | 0.18 | 0.683 |
| Error | 11 | 0.13777 | 0.01252 | | |
| Total | 15 | 4.74417 | | | |

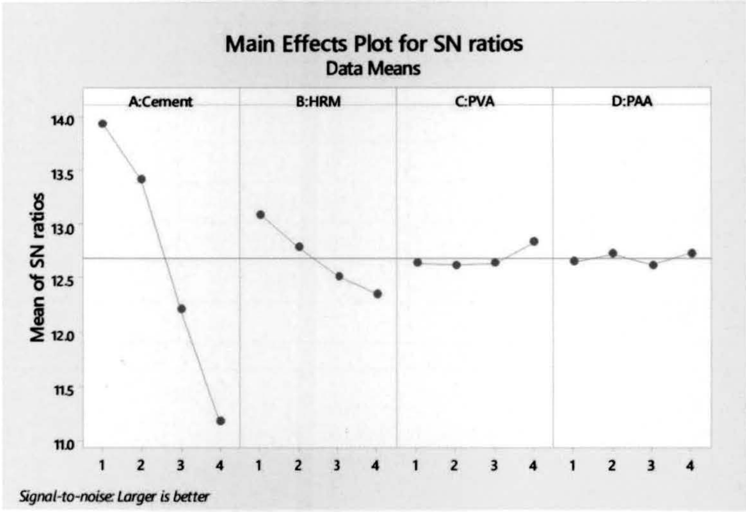



**Figure 13: Effect of Input Parameters on Split Tensile Strength at 28 Days**

**Taguchi Method and Multi-Regression Analysis**

*Compressive Strength of Optimized Mix at 28 Days*

The response factors of input parameters on compressive strength showing maximum S/N ratio are obtained from all levels of all factors at 28 days, shown in *Table 8*. As per the rank, cement and Metakaolin are the first and second factors, respectively, that influence the strength development followed by PAA and PVA. *Table 9* shows the analysis of variance using the software MINITAB 18 at 0.05 level of significance.

*Figure 11* shows the effect of input parameters on compressive strength at 28 days. It is found that input parameters Cement =430 kg/m$^3$, High reactive Metakaolin=22.5 kg/m$^3$, PVA=0.0258 kg/m$^3$ and PAA=0.0533 kg/m$^3$ provide the maximum compressive strength (Maximizing response).

**Model Summary**

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.636102 | 96.58% | 95.33% | 92.29% |

The Multi-Regression Equation for 28 days on optimized design parameters is calculated and is as follows:

fc at 28 days= 73.420 - 2.406 OPC - 0.690 HRM - 0.055 PVA - 0.120 PAA

The model proposes the equation with a degree of confidence 0.96586 (R2=96.58) and the P value less than 0.05 of cement and HRM indicates the significance of the model terms.

*Flexural Strength of Optimized Mix at 28 Days*

The response factors of the input parameters on flexural strength showing maximum S/N ratio are obtained from all levels of all factors at 28 days, as shown in *Table 10*. Considering the rank, cement and Metakaolin rank as the first and second factors respectively that significantly influence strength development followed by PAA and PVA. *Table 11* shows the analysis of variance (by using the software MINITAB 18) at 0.05 level of significance.

*Figure 12* shows the effect of input parameters on flexural strength at 28 days. It is found that input parameters Cement =430 kg/m$^3$, High reactive Metakaolin=22.5 kg/m$^3$, PVA=0.0258 kg/m$^3$ and PAA=0.0533 kg/m$^3$ provide the maximum flexural strength (Maximizing response).

**Regression Analysis:** fb at 28 days versus A: Cement, ..., C:PVA, D:PAA

**Model Summary**

| S | **R-sq** | R-sq( adj) | R-sq(pred) |
|---|---|---|---|
| 0.173008 | **92.33%** | 89.54% | 82.21% |

**Regression Equation**

**fb at 28 days** = 6.692 - 0.3922 A:Cement - 0.1763 B:HRM + 0.0557 C:PVA - 0.1002 D:PAA

The model proposes the equation with the degree of confidence at 0.9233 (R2=92.33) and the P value less than 0.05 of cement and HRM indicates the significance of the model terms.

***Split tensile Strength of Optimized Mix at 28 Days***

The response factors of the input parameters on split tensile strength showing maximum S/N ratio are obtained from all levels of all factors at 28 days, as shown in *Table 12.* Considering the rank, cement and Metakaolin rank as the first and second factors respectively that significantly influence strength development followed by PAA and PVA. *Table 13* shows the analysis of variance (by using software MINITAB 18) at 0.05 level of significance.

*Figure 13* shows the effect of the input parameters on split tensile strength at 28 days. It is found that input parameters Cement =430 $kg/m^3$, High reactive Metakaolin=22.25 $kg/m^3$, PVA=0.0258 $kg/m^3$ and PAA=0.0533 $kg/m^3$ provide the maximum split tensile strength (Maximizing response).

**Regression Analysis:** ft at 28 days versus A: Cement, ..., C:PVA, D:PAA

**Model Summary**

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.111911 | **97.10%** | 96.04% | 93.77% |

**Regression Equation**

**ft at 28 days** = 5.734 - 0.4645 A:Cement - 0.1190 B:HRM + 0.0170 C:PVA + 0.0105 D:PAA

The model proposes the equation with the degree of confidence at 0.9710 (R2=97.10) and P value slightly higher than 0.5.

The present study evaluated the mechanical properties at 28 days with the corresponding input parameters by using multi-regression analysis. The multi-regression analysis was conducted to develop a linear model of the experimental results and find the optimum combination of the design parameters. The response of each parameter suggests the rank by using more prominent is better performance characteristics. The multi-regression analysis also proposes the equations which give predicted values of all the mechanical properties.

## CONCLUSION

This experimental work was conducted using the Taguchi approach in order to demonstrate the properties of self-curing high strength concrete. Based on the work done, the following conclusions have been drawn:

It is critical to identify the most important factors that influence the properties of high strength concrete. Hence, the study suggests that the Taguchi method is a promising method to optimize the mixture proportions of self- curing high strength concrete. By this approach, the influence of each parameter on the compressive, flexural and indirect tensile strength was determined in terms of a resultant rank in the testing age of 28 days. The resultant rank for compressive strength shows that the factors cement and highly reactive Metakaolin contribute to strength development. Poly acrylic acid also shows more influence than Polyvinyl alcohol. The resultant rank of flexural and split tensile strength shows that cement is the first and HRM is the second factor influencing the strength properties. It also shows that Polyvinyl alcohol has more effect than Poly acrylic acid. It is noticeable that the presence of high reactive Metakaolin has an important role to play in the strength development of mixtures. The result shows that the compressive strength of self-cured mix is about 50-55% more than the conventional non self - cured mix. The flexural strength and split tensile strength obtained are respectively 1.7 and 1.6 times more than the strength obtained of non-cured concrete. To optimally formulate the influencing parameters, a nonlinear third order regression analysis was conducted until a relatively higher correlation coefficient (R2) was obtained. The R2 value found was more than 95%. The results obtained experimentally strongly correlate with the regression equations suggested.

## Acknowledgment

This research did not receive any specific grant from any funding agencies.

The author would like to thank Dr. S.B. Thakare for his constant encouragement and valuable guidance. Additionally, the author wants to thank the Principal and students of SBPCOE for their support in the research work.

## References

Castro et al. (2010). Internal curing Spring convention ACT.

Dhinakaran, G., Thilgavathi, S., & Venkataramana, J. (2012). Compressive strength and chloride resistance of metakaolin concrete. *KSCE Journal of Civil Engineering, 16*(7), 1209-1217

El-Dieb, A. S., El-Maaddawy, T. A., & Mahmoud, A. A. (2012). Water-soluble polymers as self-curing agents in cement mixes. *Advances in Cement Research, 24*(5), 291-299.

Espinoza-Hijazin, G., Paul, Á., & Lopez, M. (2012). Concrete containing natural pozzolans: new challenges for internal curing. *journal of materials in civil engineering*, *24*(8), 981-988.

Hong Seong Wong (2018). Eco-Efficient Repair and Rehabilitation of Concrete Infrastructures *Wood head Publishing Series* in Civil and Structural Engineering, Pages 467-49.

I.S. 13311-Part I (Nondestructive test)

IS 10262:2009 (Concrete Mix Proportioning)

IS 2386:3 1963 (Method of Test for Aggregate for Concrete)

IS 516 : 1959 cl.2,3 (Compressive Strength Test)

IS 516 : 1959 cl.7 (Flexural Strength Test)

IS: 1199–1959 (Slump Cone Test)

Islam, B., Rahman, M. S., & Noor, M. A. (2011). A state of art review on internal curing of concrete and its prospect for Bangladesh. In *Bangladesh-4th Annual Paper Meet and 1st Civil Engineering Congress* (pp. 22-28).

Kim, H. S., Lee, S. H., & Moon, H. Y. (2007). Strength properties and durability aspects of high strength concrete using Korean metakaolin. *Construction and building materials*, *21*(6), 1229-1237.

Klemm Agnieszka Joanna & Karol S. Sikora (2013). Super Absorbent Polymer Cementitious Composites Glasgow Calediniam University, Glasgow, UK. *Construction and Building Materials,* 49,134–14.

Klemm, A. J., & Sikora, K. S. (2013). The Effect of Superabsorbent Polymers (SAP) on Microstructure and Mechanical Properties of Fly Ash Cementitious Mortars. *Construction and Building Materials*, *49*, 134-143.

Lan, G., Chen, P., Sun, Q., & Fang, S. (2013). Methods for Treating Hemorrhagic Conditions. United States Patent, No. US 8,362,081 B2.

Lura, P., Guang, Y., Tanaka, K., & Jensen, O. M. (2005). Micro-Crack Detection in High-Performance Cementitious Materials. In *Fourth International Seminar on Self-desiccation and Its Importance in Concrete Technology* (pp. 165-178). Lund University of Technology.

Standard-IS, I. (1987). IS 12269-1987: Specifications for 53 Grade Ordinary Portland Cement. *New Delhi: IS.*

Structure Magazine, I. C. (2012). Constructing More Robust Concrete. *Jason Weiss, Dale Bentz, Anton Schindler, PE and Pietro Lura*, 10.

Suryawanshi, N., & Thakare, S. B. (2018). Self-Curing Assessment of Metakaolin Based High Strength Concrete Using Super Absorbent Polymer. *International Journal of Civil Engineering and Technology (IJCIET)*, *9*, 1082-87.

Türkmen, İ. I. M., Gül, R., Çel [idot] k, C., & Dem [idot] rboğa, R. (2003). Determination by the Taguchi Method of Optimum Conditions for Mechanical Properties of High Strength Concrete with Admixtures of Silica Fume and Blast Furnace Slag. *Civil Engineering and Environmental Systems*, *20*(2), 105-118.

Wild, S., Khatib, J. M., & Jones, A. (1996). Relative Strength, Pozzolanic Activity and Cement Hydration in Superplasticised Metakaolin Concrete. *Cement and Concrete Research*, *26*(10), 1537-1544.