Compressive strength and durability of Metakaolin blended concrete exposed to acid and sulphate attack

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Abstract. Sustainable development of the cement and concrete industry requires the utilization of industrial and agricultural waste components. At present, for various reasons, the concrete construction industry is not sustainable. In general, high strength concrete made with ordinary cement is not durable and does not have good resistance to acids except for some weak acids if the exposure is occasional. Metakaolin is a supplementary cementitious material used as an admixture to produce high strength and high-performance concrete. The objective of this study is to arrive at Optimal quality of metakaolin that can partially replace the cement for M20, M30, M40, M50, M60, M70, M80 grades of concrete to get better strength and durability. The mix proportions of OPC concrete are obtained for M20, M30, M40, M50, M60, M70, M80 as per IS 10262 2009 [1]. Mix proportions with partial replacements of cement by 0%, 10%, 15%, 20%, 25%, 30% of Metakaolin with concrete were determined. Concrete specimens for compressive strength (150 mm×150 mm×150 mm cubes) are cast and Durability studies are conducted for all grades with partial replacement of cement by Metakaolin for 1% and 0.5% concentrations of HCl and H₂SO₄. From the results, it was concluded that the compressive strength of concrete is maximum at 15% replacement of cement by Metakaolin. The compressive strength of concrete showed better result at 15% replacement of Metakaolin for 0.5% and 1% HCl and H₂SO₄ at the age of 28 days of strength. The effect of HCl on strength of the Metakaolin concrete is lower than the effect of H₂SO₄.

Keywords: Metakaolin; compressive strength; acid attack; sulphate attack;

1. Introduction
Sustainable development of the cement and concrete industry requires the utilization of industrial and agricultural waste components. At present, for various reasons, the concrete construction industry is not sustainable. Firstly, it consumes huge quantities of virgin materials which need to remain for the next generations. Secondly, the principal binder in concrete is Portland cement, the production of which is a major contributor to greenhouse gas emissions that is implicated to global warming and climate change. Thirdly, many concrete structures suffer from a lack of durability and thus wasting precious natural resources. So, finding a solution to substitute a part of the cement for improved durability seems to be desirable for sustainable development. Metakaolin (Al₂Si₂O₇) exhibits pozzolanic properties and hence can be used as a concrete constituent, replacing part of the cement content. Metakaolin differs from
other supplementary cementitious materials like fly ash, slag or silica fume as it is not a by-product of an industrial process. It is a fine, natural white clay manufactured by the calcination of kaolinic clay at a temperature ranging between 650°C and 850°C to particle structure making it a highly reactive, amorphous pozzolans for a specific purpose under controlled conditions.

Al-Akhras 2006 [2] studied the durability of metakaolin to sulfate attack. Bai 2002 [3] investigated the temperature change and heat evolution of mortar incorporating PFA and metakaolin. Brooks and Johari 2001 [4] studied the effect of metakaolin on creep and shrinkage of concrete. Courard et al 2003 [5] researched on the durability of mortars modified with metakaolin. Frías et al. 2000 [6] experimented on the effect of pozzolanic reaction of metakaolin on the heat evolution in metakaolin-cement mortars. Gruber et al. 2001 [7] observed that there is an increase in concrete durability with high-reactivity metakaolin. Khatib and Clay 2004 [8] experimented on the absorption characteristics of metakaolin concrete. Lee et al. 2005 [9] observed the effect of solution concentrations and replacement levels of metakaolin on the resistance of mortars exposed to magnesium sulphate solutions. Poon et al. 2001 [10] experimented on the rate of pozzolanic reaction of metakaolin in high-performance cement pastes. Poon et al. 2003 [11] studied the performance of metakaolin concrete at elevated temperatures. Qian and Li 2001 [12] studied the relationships between stress and strain for high-performance concrete with metakaolin. Ramlochan et al. 2000 [13] studied the effect of metakaolin on the alkali-silica reaction in concrete.

Many others investigated the basic mechanical and microscopic properties of cement mortar and concrete produced with partial replacement of cement with metakaolin. The reason for these improved properties of concrete was attributed to high siliceous content in metakaolin also called as High Reactivity Metakaolin (HRM). During the cement hydration process, water reacts with Portland cement and forms calcium – silicate - hydrate (C-S-H). The by-product of this reaction is the formation of calcium hydroxide (lime). This lime forms a weak link in concrete, and hence reduces the effect of the C-S-H. When Metakaolin is added in the hydration process, it reacts with the free lime to form additional C-S-H material, thereby making the concrete denser, stronger. In addition to strength, concrete has to be durable for the structures to be sustainable. The problem is more so in structures exposed to sulphate attack (seawater, sewage, industrial waste, salts in groundwater, and delayed release of clinker) and acid attack (acid rains).

Many researchers also attempted to study the effect of acid exposure on various mechanical properties of High-performance concrete made with Metakaolin blended cement concrete. They observed that partial replacement of cement by Metakaolin reduces the thickness of the interfacial zone, thus improving the adhesive bond between the hardened cement paste and particles of sand or aggregate. Metakaolin is obtained from the 20 Microns Limited Company at Vadodara in Gujarat. The specific gravity of Metakaolin is about 2.65.

Sulphate attack is caused by the chemical reaction between sulphate ions and hydration products, leading to ettringite and gypsum formation. Mono-sulphate, CH, and water combine to form ettringite. The expansive force generates tensile stresses in concrete. This leads to severe damage and cracking. Sulphuric acid (H₂SO₄) is particularly aggressive because, in addition to the sulphate attack of the aluminates phase, acid attack on Ca(OH)₂ and C-S-H takes place. Acid rains, which consists mainly of sulphuric acid and nitric acid and has a pH value between 4.0 and 4.5, may cause surface weathering of exposed concrete.

1.1. Corrosion of embedded steel in concrete
Deterioration of concrete containing embedded metals, such as conduits, pipes, and reinforcing and prestressing steel, is attributable to the combined effect of more than one cause. Corrosion of steel in concrete is an electrochemical process. The electrochemical potentials to form the corrosion cells may be generated in the following ways. Composition cells may be formed when two dissimilar metals are embedded in concrete, such as steel rebar’s and aluminium conduit pipes, or when significant variations exist in surface characteristics of the steel. Concentration cells may be formed due to differences in concentration of dissolved ions in the vicinity of steel, such as alkalies, chlorides and oxygen.
1.2. Concluding remarks on literature
It was observed from the literature survey that the experiments are not carried out on all grades. The behaviour cannot be predicted with a limited number of grades and with a little number of concrete cubes. Very little quantity of papers identified on metakaolin concrete subjected to acid attack. So, the work is framed to conduct experiments on a greater number of concrete cubes by considering arrange of grades, various percentages of metakaolin and acids for curing to model a greater number of samples and to determine the acceptable results on metakaolin concrete.

2. Objective, Scope and Methodology
This section deals with the objective, scope of the study and planning of entire work in a stepwise manner along with properties of the materials.

2.1. The objective of the study
The objective of this work is to evaluate the optimum percentage of Metakaolin replacement in cement for maximum compressive strength and durability of concrete exposed to acid and sulphate enhancement of its strength properties.

2.2. Scope of the study
The results of this experimental study are applicable, only to the effect on compressive strength of concrete, caused by the replacement of cement by Metakaolin to the extends of 0, 10, 15, 20, 25 and 30 percentage in respect of OPC. Fine aggregate passing through 4.75 mm I.S. Sieve and retained on 300 microns I.S. Sieve was used in this study. Coarse aggregate passing through 12.5 mm sieve and retained on 4.75mm sieve, was adopted. Ordinary potable water was used for mixing and curing. Immersion curing for a period of 28 days was adopted. The effect on compressive strength, caused by the replacement of cement by Metakaolin to the extends of 0%, 10%, 15%, 20%, 25%, 30% in respect of OPC and acids (for H$_2$SO$_4$ – 0.5% and 1% concentration and for HCl – 0.5% and 1% concentration) was studied.

2.3. Need for the present study
The behaviour of high strength concrete in strength and durability has been known earlier for normal and other concretes whereas, for Metakaolin blended concrete, they have not been known. Hence this study is an emphasis on mechanical properties of M20, M30, M40, M50, M70, M80 grades of concrete with partially replaced cement.

2.4. Need for the present study
Based on the preliminary investigations carried out, the experimental investigation is planned as under.
1. Find the properties of the materials such as cement, sand, coarse aggregate and Metakaolin.
2. Obtain the mix proportions of OPC concrete for M20, M30, M40 and M50 by IS method (IS 10262 2009 [1]). Entropy and Shacklock’s empirical method was adopted for mix proportioning of M60, M70 and M80.
3. Calculate the mix proportions for weight batching with partial replacements such as 0%, 10%, 15%, 20%, 25%, 30% of Metakaolin with concrete.
4. Preparation of Testing Specimens such as concrete specimens of size 150 mm × 150 mm × 150 mm for durability studies in laboratory with 0%, 10%, 15%, 20% 25% 30% replacement of OPC with Metakaolin for M20, M30, M40, M50, M60, M70 and M80 grade concrete.
5. To evaluate the 28 days compressive strength and durability (RCPT) of M20, M30, M40, M50, M60, M70 and M80 grade concrete with Metakaolin replacement exposed to 1% and 0.5% concentrations of HCl and H$_2$SO$_4$.

3. Experimental program
3.1. Material Properties
The materials used in the experimental work namely cement, Metakaolin, fine aggregate and coarse aggregate (20mm passing and 10mm retained) have been tested in the laboratory for use in the mix design. Ordinary Portland cement of 43 grade confirming to IS 8112: 1989 [14] was used in this
research. Fine Aggregate. Aggregates smaller than 4.75mm and up to 0.075mm are considered as fine aggregate. The specific gravity of fine aggregate is 2.60.

Sieve analysis to determine the particle size distribution of the coarse and fine aggregates is done by sieving the aggregates as per IS 2386 (Part 1) 1963 [15]. A set of IS Sieves of sizes- 80mm, 40mm, 20mm, 16mm, 10mm, 4.75mm, 2.36mm, 1.18mm, 600µm, 300µm and 150 µm were used for finding fineness modulus of fine and coarse aggregate. IS Sieves of sizes from 80mm to 4.75mm were used for coarse aggregate analysis and from 4.75mm to 150 µm IS sieves were used for the analysis of fine aggregates.

**Fine aggregate**

Table 1. Sieve Analysis of Fine Aggregate

| IS Sieve size (mm) | Weight retained (kgs) | Cumulative weight retained (kgs) | Cumulative % weight retained (w1) | % Passing |
|--------------------|-----------------------|----------------------------------|----------------------------------|-----------|
| 10                 | 0.005                 | 0.005                            | 0.5                              | 99.5      |
| 4.75               | 0.005                 | 0.010                            | 1                                | 99        |
| 2.36               | 0.01                  | 0.02                             | 2                                | 98        |
| 1.18               | 0.075                 | 0.095                            | 9.5                              | 90.5      |
| 0.6                | 0.16                  | 0.255                            | 25.5                             | 74.5      |
| 0.3                | 0.43                  | 0.685                            | 68.5                             | 31.5      |
| 0.15               | 0.260                 | 0.945                            | 94.5                             | 5.5       |

Table 2. Properties of Fine Aggregate

| Properties                  | Test values |
|-----------------------------|-------------|
| Specific gravity            | 2.60        |
| Bulk density (gm/cc)        | 1.68        |
| Fineness modulus            | 2.66        |

Fineness modulus = \( \frac{w_1}{100} = \frac{201.5}{100} = 2.015 \);

Hence Fine aggregate (sand) belongs to ZONE – III.

**Coarse aggregate**

Aggregates greater than 4.75mm are considered as coarse aggregate.

Table 3. Sieve Analysis of Coarse Aggregate

| IS Sieve size (mm) | Weight retained (kgs) | Cumulative weight retained (kgs) | Cumulative % weight retained (w2) | Cumulative % passing |
|--------------------|-----------------------|----------------------------------|----------------------------------|----------------------|
| 80                 | 0                     | 0                                | 0                                | 100                  |
| 40                 | 0                     | 0                                | 0                                | 100                  |
| 20                 | 1.37                  | 1.37                             | 27.4                             | 72.6                 |
| 10                 | 3.545                 | 4.915                            | 98.3                             | 1.7                  |
| 4.75               | 0.085                 | 5.0                              | 100                              | 0                    |
| 2.36               | -                     | -                                | 100                              | 0                    |
| 1.18               | -                     | -                                | 100                              | 0                    |
| 0.6                | -                     | -                                | 100                              | 0                    |
| 0.3                | -                     | -                                | 100                              | 0                    |
| 0.15               | -                     | -                                | 100                              | 0                    |
Table 4. Properties of Coarse Aggregate

| Properties                                | Test values |
|-------------------------------------------|-------------|
| Specific gravity                          | 2.64        |
| Bulk density (loose) (gm/cc)              | 1.38        |
| Bulk density (compacted)(gm/cc)           | 1.53        |

Sieve Analysis
Coarse aggregate: 20mm passed
Fine aggregate: Confirming to Zone III of Table 4 of IS 383 1970 [16]

Test data for materials.
Cement OPC 43 grade
Specific Gravity of Cement 3.15
Specific Gravity of Coarse Aggregate 2.71
Specific Gravity of Fine Aggregate 2.52
Specific Gravity of Water 1
Water Absorption of 20 mm Aggregate 0.5%
Water Absorption of Sand 1.0%
Free (Surface) Moisture of 20 mm Aggregate/Sand Nil

3.2. Manufacturing of concrete and its workability
Concrete is mixed, placed, compacted, cured, de-moulded and tested.

3.3 Tests on workability
Slump cone test. Slump cone test is a very common test for determination of workability of concrete. This test was carried out for M80, before casting the specimens.
Compaction Factor Test. This test is more accurate than slump cone test and this test is used to determine the workability of low water-cement ratio concrete more accurately. This test is conducted as per IS 1199 1959 [16].

Table 5. Compaction Factor Values

| Description               | M20 | M30 | M40 | M50 | M60 | M70 | M80 |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|
| Plain Concrete            | 0.94| 0.92| 0.89| 0.88| 0.87| 0.86| 0.84|
| Metakaolin 10%            | 0.89| 0.88| 0.87| 0.86| 0.84| 0.83| 0.82|
| Metakaolin 15%            | 0.88| 0.87| 0.86| 0.84| 0.83| 0.81| 0.80|
| Metakaolin 20%            | 0.87| 0.86| 0.84| 0.82| 0.80| 0.79| 0.78|
| Metakaolin 25%            | 0.86| 0.85| 0.83| 0.80| 0.79| 0.76| 0.75|
| Metakaolin 30%            | 0.85| 0.84| 0.81| 0.79| 0.76| 0.74| 0.72|

Table 6. Slump Cone Values

| Description               | M20 | M30 | M40 | M50 | M60 | M70 | M80 |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|
| Plain Concrete            | 40  | 38  | 34  | 30  | 26  | 22  | 20  |
| Metakaolin 10%            | 35  | 33  | 30  | 26  | 24  | 20  | 18  |
| Metakaolin 15%            | 33  | 28  | 26  | 23  | 19  | 17  | 15  |
| Metakaolin 20%            | 30  | 26  | 20  | 19  | 17  | 14  | 13  |
| Metakaolin 25%            | 28  | 25  | 23  | 19  | 17  | 14  | 11  |
| Metakaolin 30%            | 26  | 21  | 19  | 17  | 14  | 12  | 10  |
4. Results and Discussions

This section deals with the analysis of the results after conduction of compression test concrete cube specimens. Discussions are made by comparing the results between with and without Metakaolin variation in acids by keeping a control specimen as reference.

4.1. Compressive strength

Determination of Compressive Strength for Different Grades with variation in % of Metakaolin for 28 and 90 days.

4.1.1. Compressive strength for 28 days.

For M20 grade concrete % increase of compressive strength for replacement of cement with Metakaolin by 10% is 6.81%, 15% is 12.58%, 20% is 4.86%, 25% is 3.03% with respect to control specimen (0% Metakaolin at 27°C curing). The % decrease in compressive strength of replacement of cement with Metakaolin by 30% is 0.39% for control specimen (0% Metakaolin at 27°C curing).

For M30 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 4.42%, 15% is 12.10%, 20% is 9.94%, 25% is 5.6%, 30% is 1.98% with respect to control specimen (0% Metakaolin at 27°C curing).

For M40 grade concrete % in compressive strength for replacement of cement with Metakaolin by 10% is 3.34%, 15% is 11.66%, 20% is 9.20%, 25% is 4.64%, and 30% is 0.74% with respect to control specimen (0% Metakaolin at 27°C curing).

For M50 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 1.69%, 15% is 3.38%, 20% is 3.38%, 25% is 6.25%, 30% is 7.30% with respect to control specimen (0% Metakaolin at 27°C curing).

For M60 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 2.61%, 15% is 9.02%, 20% is 8.36%, 25% is 4.29%, 30% is 0.89% with respect to control specimen (0% Metakaolin at 27°C curing).

For M70 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 1.69%, 15% is 3.38%, 20% is 3.38%, 25% is 6.25%, 30% is 7.30% with respect to control specimen (0% Metakaolin at 27°C curing).

For M80 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 9.13% and 15% is 11.68%, 20% is 6.60% to control specimen (0% Metakaolin at 27°C curing). The % decrease in compressive strength for replacement of cement with Metakaolin by 20% is 3.34%, 25% is 9.49% and 30% is 13.96% to control specimen (0% Metakaolin at 27°C curing).

Figure 1. Compressive Strength for Different Grades with Variation in % of Metakaolin for 28 days curing to control specimen (0% Metakaolin at 27°C curing).

For all grades, the compressive strength increases with the replacement of cement by Metakaolin up to 15% and then decreases. Maximum compressive strength of 11.68% is obtained for M80 grade concrete with replacement of cement by 15% Metakaolin for 28 days curing to control specimen (0% Metakaolin at 27°C curing).
4.1.2. *Compressive strength for 90 days.*

For M20 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 8.64%, 15% is 17.44%, 20% is 14.82%, 25% is 12.47%, 30% is 5.59% with respect to control specimen (0% Metakaolin at 27°C curing) and respectively.

For M30 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 6.74%, 15% is 19.0%, 20% is 15.73%, 25% is 8.35%, 30% is 1.93% with respect to control specimen (0% Metakaolin at 27°C curing).

For M40 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 5.10%, 15% is 11.25%, 20% is 7.17%, 25% is 0.16%, and 30% is 0.40% with respect to control specimen (0% Metakaolin at 27°C curing).

For M50 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 1.63% 15% is 3.27%, 20% is 4.91%, 25% is 2.57%, 30% is 6.36% with respect to control specimen (0% Metakaolin at 27°C curing).

For M60 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 6.99%, 15% is 11.20%, 20% is 4.41%, 25% is 2.65%, 30% is 3.66% with respect to control specimen (0% Metakaolin at 27°C curing).

For M70 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 3.06%, 15% is 23%, 20% is 5.37%, 25% is 2.96% and 30% is 1.42% with respect to control specimen (0% Metakaolin at 27°C curing).

For M80 grade concrete % increase in compressive strength for replacement of cement with Metakaolin by 10% is 3.00%, 15% is 10%, 20% is 7.56%, 25% is 2.24% and slightly decreased for 30% is 0.50% with respect to control specimen (0% Metakaolin at 27°C curing).

For each grade, the compressive strength increases with the replacement of cement by Metakaolin up to 15% and then decreases. Maximum compressive strength of 10.00% is obtained for M80 grade concrete with replacement of cement by 15% Metakaolin for 90 days curing to control specimen (0% Metakaolin at 27°C curing).

![Figure 2. Compressive Strength for Different Grades with Variation in % of Metakaolin for 90 days](image)

**4.1.3. Summary of effect of Metakaolin on Compressive Strength of Concrete.**

It is observed that at 15% replacement of cement with Metakaolin, concrete attains its maximum compressive strength to all grades (M20 - M80) for both 28 days and 90 days curing. When the replacement exceeds 15% with Metakaolin, the compressive strength is found to be decreasing slightly. The reduction in compressive strength for above 15% replacement of Metakaolin, when compared to Metakaolin with 10%, is expecting because of the result of a clinker dilution effect. The dilution effect is a result of replacing a part of cement by the equivalent quantity of Metakaolin. In Metakaolin concrete, the filler effect, the pozzolanic reaction of Metakaolin with calcium hydroxide and
compounding effect (synergetic effect of mineral admixture) react opposite of the dilution effects Metakaolin improves the pozzolanic reaction by filler effect and accelerate the hydration of cement.

4.1.4. Effect of compressive strength with variation in acid of 0.5% HCl (Grade vs. % of Metakaolin).

The % decrease of compressive strength with the addition of 0.5% HCl for M20 grade concrete, replacement of cement with Metakaolin by 0% is 6.6% respectively. The % increase for 10% is 0.8% and 15% is 5.8% respectively. The % decrease for 20% is 1.14%, 25% is 2.31%.

The % decrease of compressive strength with the addition of 0.5% HCl for M30 grade concrete, replacement of cement with Metakaolin by 0% is 5.37%. The % decrease for 10% is 0.41%. The % increase for 15% is 6.70%, 20% is 5.10%, 25% is 1.30% when compared with control specimen (normal water curing). The % decrease for 30% is 2.85% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with the addition of 0.5% HCl for M40 grade concrete, replacement of cement with Metakaolin by 0% is 4.44%. The % decrease for 10% is 0.66%. The % increase for 15% is 7.20%, 20% is 5.20%, 25% is 1.08%. The % decrease for 30% is 3.26% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with the addition of 0.5% HCl for M50 grade concrete, replacement of cement with Metakaolin by 0% is 3.76%. The % decrease for 10% is 1.35%. The % increase for 15% is 1.67%. The % decrease for 20% is 6.52%, 25% is 9.27%, 30% is 10.69% respectively when compared with control specimen (normal water curing).

There is no change in compressive strength with the addition of 0.5% HCl for M60 grade concrete, replacement of cement with Metakaolin by 0%. The % increase of compressive strength for replacement of cement with Metakaolin by 10% is 2.61%, 15% is 9.02%, 20% is 8.36%, 25% is 4.29%, 30% is 0.89% respectively when compared with control specimen (normal water curing).

The % loss of compressive strength with the addition of 0.5% HCl for M70 grade concrete, replacement of cement with Metakaolin by 0% is 2.79%. The % increase for 10% is 4.75%, 15% is 6.70%. The % decrease for 20% is 5.85%, 25% is 11.72%, 30% is 16.48% respectively when compared with control specimen (normal water curing).

The % loss of compressive strength with the addition of 0.5% HCl for M80 grade concrete for replacement of cement with Metakaolin by 0% is 6.85%. The % increase for 10% is 9.13%, 15% is 4.31%. The % decrease for 20% is 3.03%, 25% is 7.35%, 30% is 22.06% respectively when compared with control specimen (normal water curing).

For each grade, the compressive strength increases with increase in % of Metakaolin up-to 15% and then decreases. The maximum compressive strength for 0.5% HCl curing is obtained for M80 grade concrete as 5.8% with the replacement of cement by 15% Metakaolin when compared with control specimen (normal water curing).

![Figure 3. Effect of Compressive Strength with Variation in % of Metakaolin for 0.5% of HCl (% of Metakaolin vs. grade)](image-url)
4.1.5. Effect of compressive strength with variation in acids 1% HCL (Grade vs % of Metakaolin)

The % loss of compressive strength with addition of 1% HCl for M20 grade concrete, replacement of cement with Metakaolin by 0% is 13.33%, 10% is 6.51%, 15% is 0.78%, 20% is 8.46%, 25% is 8.97%, 30% is 13.06% respectively when compared with control specimen (normal water curing).

The % loss of compared with compressive strength with the addition of 1% HCl for M30 grade concrete, replacement of cement with Metakaolin by 0% is 10.74%. The % decrease of compressive strength for replacement of cement with Metakaolin by 10% is 6.31%. The % increase of compressive strength for replacement of cement with Metakaolin by 15% is 1.33%. The % decrease of compressive strength for replacement of cement with Metakaolin by 20% is 0.79%, 25% is 4.06%, 30% is 8.22% respectively when compared with control specimen (normal water curing).

The % loss of compressive strength with addition of 1% HCl for M40 grade concrete, replacement of cement with Metakaolin by 0% is 8.0%. The % increase for 10% is 3.34%, 15% is 11.66%, 20% is 9.20%, 25% is 4.64% 30% is 0.74% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with addition of 1% HCl for M50 grade concrete, for replacement of cement with Metakaolin by 0% is 7.52%. The % decrease for 10% is 5.49%, 15% is 2.76%, 20% is 10.66%, 25% is 13.03%, 30% is 14.45% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with the addition of 1% HCl for M60 grade concrete, replacement of cement with Metakaolin by 0% is 6.98%. The % decrease by 10% is 4.37%. The % increase of compressive strength for replacement of Metakaolin in cement by 15% is 2.02%, 20% is 1.38%, % decrease for 25% is 1.99%, 30% is 5.74% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with the addition of 1% HCl for M70 grade concrete, replacement of cement with Metakaolin by 0% is 5.02%. The % increase of compressive strength for replacement of cement with Metakaolin 10% is 0.98%, 15% is 3.90%. The % decrease for 20% is 8.92%, 25% is 14.51%, 30% is 19.27% respectively when compared with control specimen (normal water curing).

The % loss of compressive strength with addition of 1% HCl for M80 grade concrete, replacement of cement with Metakaolin by 0% is 5.07%. The % increase for 10% is 4.06%, 15% is 6.60%, 20% is 1.53%. The % decrease for 25% is 5.57%, 30% is 9.89% respectively when compared with control specimen (normal water curing).

For each grade, the compressive strength increases with increase in % of Metakaolin up-to 15% and then decreases. The maximum compressive strength for 1% HCl curing is obtained for M80 grade concrete as 6.60% with the replacement of cement by 15% Metakaolin when compared with control specimen (normal water curing).

![Figure 4. Effect of Compressive Strength with Variation in % of Metakaolin for 1% of HCl (% of Metakaolin vs. grade)](image-url)
4.1.6. Effect of compressive strength with variation in acids 0.5% \( \text{H}_2\text{SO}_4 \) (Grade vs % of Metakaolin).

The % decrease of compressive strength with addition of 0.5% \( \text{H}_2\text{SO}_4 \) for M20 grade concrete, replacement of cement with Metakaolin by 0% is 19.33%, 10% is 11.86%, 15% is 8.10%, 20% is 15.13%, 25% is 15.01%, 30% is 19.06% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with addition of 0.5% \( \text{H}_2\text{SO}_4 \) for M30 grade concrete, replacement of cement with Metakaolin by 0% is 15.58%, 10% is 10.62%, 15% is 4.57%, 20% is 6.17%, 25% is 8.93%, 30% is 13.06% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with addition of 0.5% \( \text{H}_2\text{SO}_4 \) for M40 grade concrete, replacement of cement with Metakaolin by 0% is 12.88%, 10% is 9.10%, 15% is 2.12%, 20% is 4.12%, 25% is 7.38%, 30% is 11.70% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with addition of 0.5% \( \text{H}_2\text{SO}_4 \) for M50 grade concrete, replacement of cement with Metakaolin by 0% is 10.91%, 10% is 8.50%, 15% is 6.89%, 20% is 14.42%, 25% is 16.44%, 30% is 17.84% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with addition of 0.5% \( \text{H}_2\text{SO}_4 \) for M60 grade concrete, replacement of cement with Metakaolin by 0% is 10.13%, 10% is 7.17%, 15% is 1.80%, 20% is 2.10%, 25% is 5.15%, 30% is 8.88% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with addition of 0.5% \( \text{H}_2\text{SO}_4 \) for M70 grade concrete, replacement of cement with Metakaolin by 0% is 8.09%, 10% is 0.55%, % increase for 15% is 0.84%, % decrease for 20% is 11.71%, 25% is 9.49%, 30% is 13.96% respectively when compared with control specimen (normal water curing).

The % decrease of compressive strength with addition of 0.5% \( \text{H}_2\text{SO}_4 \) for M80 grade concrete, replacement of cement with Metakaolin by 0% is 7.35%. The % increase for 10% is 2.03%, 15% is 3.81%. The % decrease for 20% is 1.00%, 25% is 7.86%, 30% is 12.17% respectively when compared with control specimen (normal water curing).

For each grade, the compressive strength increases with increase in % of Metakaolin up-to 15% and then decreases. The maximum compressive strength for 0.5% \( \text{H}_2\text{SO}_4 \) curing is obtained for M80 grade concrete as 3.81% with replacement of cement by 15% Metakaolin when compared with control specimen (normal water curing).

![Figure 5](image-url)  

**Figure 5.** Effect of Compressive Strength with Variation in % of Metakaolin for 0.5% of \( \text{H}_2\text{SO}_4 \) (% of Metakaolin vs. grade)
4.1.7. Effect of compressive strength with variation in acids 1% H$_2$SO$_4$ (Grade vs % of Metakaolin)

The % loss of compressive strength with addition of 1% H$_2$SO$_4$ for M20 grade concrete, replacement of cement with Metakaolin by 0% is 35.34%, 10% is 29.21%, 15% is 24.80%, 20% is 30.51%, 25% is 31.68%, 30% is 33.09% respectively when compared with control specimen (normal water curing).

The % loss of compressive strength with addition of 1% H$_2$SO$_4$ for M30 grade concrete, replacement of cement with Metakaolin by 0% is 28.48%, 10% is 10.09%, 15% is 18.03%, 20% is 18.56%, 25% is 22.36%, 30% is 24.37% respectively when compared with the % loss of compressive strength with addition of 1% H$_2$SO$_4$ for M40 grade concrete, replacement of cement with Metakaolin by 0% is 23.54%, 10% is 20.66%, 15% is 13.24%, 20% is 14.36%, 25% is 18.48%, 30% is 21.04% respectively when compared with control specimen (normal water curing).

The % loss of compressive strength with addition of 1% H$_2$SO$_4$ for M50 grade concrete, replacement of cement with Metakaolin by 0% is 19.94%, 10% is 18.30%, 15% is 16.32%, 20% is 23.10%, 25% is 25.84%, 30% is 25.76% respectively when compared with control specimen (normal water curing). The % loss of compressive strength with addition of 1% H$_2$SO$_4$ for M60 grade concrete, replacement of cement with Metakaolin by 0% is 18.51%, 10% is 16.26%, 15% is 10.55%, 20% is 10.16%, 25% is 13.89%, 30% is 16.23% respectively when compared with control specimen (normal water curing).

The % loss of compressive strength with addition of 1% H$_2$SO$_4$ for M70 grade concrete, replacement of cement with Metakaolin by 0% is 14.79%, 10% is 7.81%, 15% is 6.14%, 20% is 18.15%, 25% is 24.02%, 30% is 27.79% respectively when compared with control specimen (normal water curing). The % loss of compressive strength with addition of 1% H$_2$SO$_4$ for M80 grade concrete, replacement of cement with Metakaolin by 0% is 7.35%. The % increase for 10% is 2.03%, 15% is 3.81%. The % decrease for 20% is 1.00%, 25% is 7.86%, 30% is 12.17% respectively when compared with control specimen (normal water curing).

For each grade, the compressive strength increases with increase in % of Metakaolin up-to 15% and then decreases. The maximum compressive strength for 1% H$_2$SO$_4$ curing is obtained for M 80 grade concrete as 3.81% with the replacement of cement by 15% Metakaolin when compared with control specimen (normal water curing).

![Figure 6. Effect of Compressive Strength with Variation in % of Metakaolin for 1% of H$_2$SO$_4$ (Grade vs. Metakaolin)](image)

4.1.8. Summary on Effect of Acids on Compressive Strength of Concrete. It was observed that ordinary Portland Cement (OPC) is highly alkaline in nature and having the pH values above 12. So, whenever the concrete or matrix paste comes into contact with the acids. The reaction between the concrete and acid will start and finally leads to the disintegration of its components If pH decreases to values lower than stability limits of cement hydrates, then the corresponding hydrate loses calcium and decomposes to the amorphous hydrogel. The final reaction products of acid attack are the corresponding calcium...
salts of the acid besides hydrogels of siliceous, aluminium, and ferric oxides. Concrete is susceptible to acid because of its alkaline nature. The components of the cement paste break during contact with acids.

5. Conclusions

Based on the analysis of experimental results and discussions the following conclusions are made.

1. Maximum compressive strength of 11.68% and 10.00% is obtained for M80 grade concrete with replacement of cement by 15% Metakaolin for 28 days curing and 90 days curing to control specimen (0% Metakaolin at 27°C curing).

2. The maximum compressive strength for 0.5% HCl, 1% HCl curing is obtained for M80 grade concrete as 5.8%, 6.60% with the replacement of cement by 15% Metakaolin when compared with control specimen (normal water curing). The maximum compressive strength for 0.5% H₂SO₄, 1% H₂SO₄ curing is obtained for M80 grade concrete as 3.81%, 3.81% with the replacement of cement by 15% Metakaolin when compared with control specimen (normal water curing).

Summary

The compressive strength of concrete is maximum at 15% replacement of cement by Metakaolin. The compressive strength of concrete showed better result at 15% replacement of Metakaolin for 0.5% and 1% HCl and H₂SO₄ at the age of 28 days of strength. The effect of HCl on strength of the Metakaolin concrete is lower than the effect of H₂SO₄.

The structures that exposed to the severe acidic environment should be given special attention while designing the structure, especially while selecting the concrete compositions and a higher safety factor should be adopted. If possible, special types of cement should be allowed reducing the deterioration effect due to the harsh acidic environment. Acidic curing environment hurts the compressive strength and density of the concrete. The rate of reduction of compressive strength for a lower concentration of acid (5%) which decreases as the concentration is raised from 5% to 10%. The compressive strength is lower at a higher concentration of acid irrespective of the type of acid and method of attack. In case of concrete structures which have to perform in an acidic environment, particular attention should be given to the design, a higher factor of safety almost double for strength should be used and if feasible, special admixtures to mitigate the effect of the acidic environment should be recommended.

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