STM JOURNALS

Recent Trends in Civil Engineering & Technology
ISSN: 2249-8753 (Online), ISSN: 2321-6476 (Print)
Volume 7, Issue 2
www.stmjournals.com

Strength and Durability Properties of Metakaolin Amalgamated High Performance Concrete

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Abstract

In past three decades, it is inevitably for the development of high strength concrete (HSC) and high performance concrete (HPC) is progressively enhanced, since these concrete are widely used throughout the world in most prominent projects like oil, bridges, multi-storey buildings and nuclear industries etc. In meticulous, the amalgamation of supplementary cementing material (SCM) or pozzolanic materials is vital when high strength and durability become the most desired properties of HPC. Metakaolin (MK) is found to be superior than other SCMs like silica fume, slag and fly ash etc. Owing to its high pozzolanic activity, both strength and durability of concrete are augmented. Also, now a day the availability of natural sand which is the main constituent of concrete is becoming complicated because of its paucity. With the exploit of locally collected waste sand i.e., crusher wash sand (CWS) as an alternative for natural sand to produce HSC/HPC may solve the problem. This paper pact with the swot of principal characteristics such as workability, mechanical properties (i.e., compressive, tensile and flexural strength) and durability of HPC for a sole water/binder ratio of 0.3. M50 grade of HPC mix was used for this study with partial replacement of cement by MK at diverse percentage ranges between 5 and 15% i.e., with every increment of 2.5% and also with 100% replacement of natural sand by crusher wash sand. MK concrete test results are compared with the reference mix (RM) (i.e., Normal HPC concrete with 100% replacement of sand by CWS). From the test results, it was observed that up to 10% increment of MK level, the mechanical properties were increased and after that the mechanical properties were decreased, but it lingered higher than the reference mix. Predominantly it was scrutinized that, 10% replacement level was the optimum level in all aspects of investigation. HPC mixes have also indicated better resistance to the attacks of chemicals such as chlorides and sulphates when the HPC mixes were exposed for a period of 180 days.

Keywords: *High performance concrete, metakaolin, crusher wash sand, pozzolanic*

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INTRODUCTION

Concrete is the most widely used construction material throughout the world with annual consumption exceeding 100 million cubic metres, and also it is used to resist the compressive forces [1]. It is well known that conventional concrete designed on the basis of compressive strength does not meet many functional requirements such as impermeability, resistance to frost, thermal cracking etc. To prevail this situation, the construction industry has taken considerable strides forward over the last three decades with regard to many materials, in particular HSC and HPC materials and also they are well positioned for increasing proliferation in use for the future [2].

In 1993, the American Concrete Institute (ACI) published a broad definition for HPC and is defined as the concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using only the conventional materials, normal mixing, placing and curing practices. The requirements may involve enhancements of placement and compaction without segregation, long-term mechanical properties, early age strength, toughness, volume stability or service life in severe environments. Concretes possessing many of these characteristics often achieve higher strength [3, 4]. Therefore, HPC is often of high strength, but HSC may not necessarily be of high performance.

Many modern concrete mixes are modified with addition of admixtures, which improve the development of concrete industry, due to the consideration of cost saving, energy saving, environmental protection and conservation of resources [4, 5]. But today, most mineral admixtures used in construction industry throughout the world are by products from other industries such as fly ash, blast furnace slag, rice husk ash, silica fume and MK which is the development of HPC mixes [4, 6–8]. MK is a leader among a new generation of such materials and unlike other SCMs, it is not a by-product of an industrial process; it is manufactured from high-purity kaolin clay by calcination at a temperature range of 650 to 900°C under controlled conditions. Its composition consists of 50 to 55% SiO_2 and 40 to 45% Al_2O_3, white appearance gives it an aesthetic appearance over other SCMs, and performance is relatively consistent [7–9]. MK is ground to an average particle size of 1.5 to 2.5 μm, which contains the highest content of siliceous, so it is called as high reactivity metakaolin [10].

Due to its high surface area and high reactivity, relatively small addition rates of MK (typically 5 to 15% replacement of cement by weight) can improve assorted concrete properties such as workability, mechanical properties, greater durability, resistance to crack and lower permeability [11, 12]. When MK is used as a partial replacement substance for cement in concrete, it reacts with $Ca(OH)_2$, one of the by-products of hydration reaction of cement and results in additional C-S-H gel which results in increased strength and reduced porosity and therefore improved durability [7, 13].

Hence by partially replacing cement with MK not only reduces carbon dioxide emissions but also increases the service life of buildings [13, 14]. The objective of this study was to investigate the effect of using MK as pozzolana on the development of high strength and permeability/durability characteristics of concrete designed for a very low w/b ratio of 0.3. In addition, the optimum replacements with respect to strength and durability were determined by varying the amount of MK as partial cement replacement.

EXPERIMENTAL PROGRAM

Materials Used

Cement

Physical and chemical properties of cement play a vital role in developing strength and controlling rheology of fresh concrete. Generally the use of high grade cements offer many advantages such as for making stronger concrete, savings in cement consumption and faster rate of development of strength etc. Because of this reason, ordinary Portland cement (OPC) of 53 grade (i.e., Ultra tech) cement conforming to IS 12269-1987 was used throughout this investigation [15]. The different laboratory tests were conducted on cement to determine the specific gravity, standard consistency, initial and final setting time as per IS 4031-1988. The above test results are tabulated in Table 1.

Table 1: *Physical Properties of OPC (53 Grade).*

Properties		Test Results	Permissible Limit as per IS 4031-1988
Specific gravity		3.14	3.1–3.15
Standard consistency		28%	26–33%
Setting time	Initial	35 min	Should not be less than 30 min
	Final	580 min	Should not be more than 600 min

Fine Aggregate (FA)

Because of the scarcity of river sand, the CWS which is collected at Madurai quarry was used as fine aggregate. It has a specific gravity and fineness modulus as 2.58 and 3.62 as per IS 2386-1963, it confirms to grading zone-II as per IS 383-1970 specification [16, 17].

Coarse Aggregate (CA)

Aggregates are the important constituents in concrete. The mere fact that the aggregates occupy 70 to 80% of the volume of concrete, cement is the only factory made component in concrete, other ingredients namely water and aggregates are natural materials and can vary to any extent in many of their properties. The crushed granite aggregates were collected from the local quarry of 20 mm and below 20 mm size. The specific gravity and fineness modulus of coarse aggregates were tested as per IS 2386-1963 and IS 383-1970 specifications and it is found to be 2.58 and 3.70 respectively [16, 17].

Mineral Admixture
MK was obtained from the English Clay Limited Company at Cochuveli in Trivandrum. The MK was in conformity with the general requirements of pozzolana as per IS 1727-1967 standards [18]. The physical and chemical properties of MK are given in Tables 2 and 3.

Chemical Admixture
It is very difficult to produce concretes without super-plasticizers, with the most ordinary Portland cements, if the water/binder ratio is less than 0.40 [19], it is based on the fact that, super plasticizer/high range water reduction agent (HRWRA) used here is Glenium B233. It was obtained from BASF Chemical Company Ltd., Mumbai. The test results of super plasticizer (SP) are shown in Table 4 as per IS 9103-1999 [20].

Water
Ordinary potable water which is free from organic content, turbidity and salts was used for mixing and for curing throughout this investigation. The test results are tabulated in Table 5, and also all the results fell within the permissible limits as per IS 3025-1964 code specification [21].

Mix Proportion
In this study, the early age properties of fresh concrete, mechanical properties and durability of hardened concrete were examined. The proportion of the materials by weight for M50 grade of concrete was found out as 1:0.66:2.03 (Cement: FA: CA) as per 10262-2009 [22]. The mixes M1, M2, M3, M4, M5 and M6 were obtained by replacing of cement with 0, 5, 7.5, 10, 12.5 and 15% of MK.

In each mix, water cementitious materials ratio was fixed at 0.30 and the fine and coarse aggregate are kept constant. A total of 90 concrete specimens were tested for finding out the mechanical properties and 18 concrete specimens for finding out the durability of concrete. All the concrete specimens such as cubes, cylinders and prisms were cast using steel moulds.

The cube specimen were used for compressive strength and durability study, cylinder specimens were used to determine split tensile strength and prisms were used to determine flexural strength of concrete. The concrete specimens are designated and it is shown in Table 6.

Table 2: *Physical Properties of MK.*

Particulars	Test Results	Codal Permissible Values
Appearance	Off-white powder	Off-white powder
pH (10% solids)	6.34	5–8
Bulk density (kg/l)	0.34	0.27–0.37
Specific gravity	2.63	2.5–2.7
Particle Size: D50 (μ)	1.97	1.5–2
Oil absorption (g/100 g)	53.48	45–65

Table 3: *Chemical Properties of Cement and MK.*

Chemical Composition	Mass of Cement (%)	Mass of MK (%)
Silicon dioxide (SiO_2)	20.10	52.00
Aluminum Oxide (Al_2O_3)	4.74	41.00
Ferrous Oxide (Fe_2O_3)	3.30	1.30
Calcium Oxide (CaO)	63.77	0.27
Magnesium Oxide (MgO)	1.05	0.38
Titanium oxide (TiO_2)	N/A	0.73
Potassium Oxide (K_2O)	0.92	0.03
Sodium Oxide (Na_2O)	0.10	0.10
Sulphur trioxide (SO_3)	3.07	-
Loss On Ignition (LOI)	1.30	1.50

Table 4: *Properties of Glenium B233.*

Mineral Content	Test Results	Codal Permissible Values
Physical state	Light brown liquid	Light brown liquid
Chemical name of active ingredient	Polycarboxylate polymer	Polycarboxylate polymer
Relative density	1.08	1.09+/–0.02
pH	6.62	6 (min)
Chloride ion content (%)	0.003	0.2 (max)
Dry material content (%)	33.71	34+/–5
Specific gravity	1.09	-

Table 5: *Properties of Water.*

Mineral Content	Results	Permissible Limit as per IS 3025-1986
pH	7	6–8
Chloride	62 mg/l	Should not be more than 500 mg/l
Sulphate	4 mg/l	Should not be more than 400 mg/l
Acidity	Nil	Should not be more than 780 mg/l

Table 6: *Detail of Concrete Mixes in kg/m³.*

Ingredients	Mixes					
	Reference mix	**MK 5%**	**MK 7.5%**	**MK 10%**	**MK 12.5%**	**MK 15%**
	M1	**M2**	**M3**	**M4**	**M5**	**M6**
OPC	600	570	555	540	525	510
MK	-	30	45	60	75	90
Water	180	180	180	180	180	180
FA	394	394	394	394	394	394
CA	1220	1220	1220	1220	1220	1220
SP	6	6	6	6	6	6
Slump (mm)	100	90	80	70	60	45
Density	2535	2480	2467	2450	2435	2412

Testing of Specimens

The workability of concrete was studied by conducting slump test as per IS 1199-1959 specification. Testing of hardened concrete plays an important role in controlling and confirming the quality of concrete works. Generally, strength of concrete is its resistance to rupture and it is measured in many ways such as strength in compression, in tension, in shear or in flexure etc.

Generally in concrete, the strength enhancement is probably due to a combination of the filler effect and accelerated cement hydration [23]. But the strength may be affected by many factors such as w/c ratio, grading of aggregate, shape of aggregate, maximum size of aggregate etc. The compressive strength of different mixes was found out at 7, 14 and 28 days whereas tensile strength and flexural strength were found out at 28 days to find the mechanical properties of concrete.

Compression Strength

Compressive strength of concrete is one of the most important and useful properties of concrete, since most of the desirable characteristic properties of concrete are qualitatively related to its compressive strength only [24]. This test was carried out on cube moulds of size 150×150×150 mm size as per IS:516-1959 specification [25]. All the moulds were cleaned thoroughly and then properly oiled along its faces before placing the concrete on moulds. Concrete was mixed properly and placed, well compacted as per the standard specifications and after that the cube specimen should be cured for testing days properly in a clean water bath.

For each mix, nine number of cube specimens were cast and tested using 2000 kN capacity compression testing machine to determine the 7th, 14th and 28th day of compressive strength. The specimen was placed on the platform of compression testing machine as shown in Figure 1. The load was applied gradually until the failure stage. The ultimate load was noted and calculated the compressive strength of corresponding specimen.

Fig. 1: *Compressive Strength of Concrete.*

$$\text{Compressive strength } (\text{N/mm}^2) = \frac{\text{Failure load (N)}}{\text{Area of cross section of specimen } (\text{mm}^2)}$$

Split Tensile Test

This is a method of determining the tensile strength of concrete using a cylinder specimen of size 150 mm diameter and 300 mm height as per IS: 5816-1999 specification [26]. It is expressed as the minimum tensile stress needed to split the specimen across the vertical diameter. All the moulds were cleaned thoroughly and then properly oiled along its inner surfaces before placing the concrete on moulds. Concrete was mixed properly, placed, well compacted and after that the specimen should be cured for 28 days properly in a clean water bath.

For each mix, nine number of specimens were cast and tested using 2000 kN capacity compression testing machine to determine the tensile strength of concrete. The specimen was placed perpendicular to normal axis on the platform of compression testing machine as shown in Figure 2. The load was applied gradually until the failure stage. The ultimate load was noted and calculated the tensile strength of corresponding specimen.

$$\text{Split tensile strength } (\text{N/mm}^2) = \frac{2P}{\pi DL}$$

Where,
P: Load at which the specimen fails (N),
D: Diameter of cylinder (mm), and
L: length of cylinder (mm).

Flexure Strength

The determination of flexure strength is essential to estimate the load at which concrete member may crack. It is the ability of a beam to resist failure in bending. Generally, the flexural strength of concrete is 12 to 20% of compressive strength and in recent days, flexural strength is not used to determine field control, only compressive strength is easy to judge the quality of concrete. The flexural test was carried in beam/prism specimen of size as 500×100×100 mm as per IS:516-1959 specification [25]. The moulds were cleaned thoroughly and then properly oiled along its inner surfaces before placing the concrete on moulds. Concrete was mixed properly, placed, well compacted as per the standard specifications and after that the cube specimen should be cured for 28 days properly in a clean water bath. For each mix, nine number of specimens were cast and tested using 400 kN capacity universal testing machine. Specimen was placed on flexure testing machine as shown in Figure 3, the load was applied gradually until the failure stage and flexural strength was calculated.

$$\text{Flexural strength } (\text{N/mm}^2) = \frac{3PL}{2BD^2}$$

Where,
P: Load at which the specimen fails (N),
L: Length of beam (mm),
B: Breadth of the beam (mm), and
D: Depth of beam (mm).

Fig. 2: *Tensile Strength of Concrete.*

Fig. 3: *Flexure Strength of Concrete.*

Durability Test on Concrete

Durability depends not only on the quality of the surface layer but also on the nature of pore system present in the concrete, because it affects the rate at which the gaseous or liquid penetrate from the external environment into the internal structure of concrete. Here, the durability is indirectly measured by the permeability test on concrete. This test was carried out on cube moulds of size 150×150×150 mm size as per IS:3085-1965 specification. Concrete was mixed properly, placed, well compacted and after that the specimen should be cured for 28 days properly in a clean water bath. After 28 days curing period, the specimens were kept immersed in 3.5% NaCl and 5% $MgSO_4$ solution for a period of 180 days [4].

The specimen was placed on the platform of compression testing machine, then the load was applied gradually until the failure stage. The ultimate load was noted and the average compressive strength of three specimens is determined.

RESULTS AND DISCUSSIONS

Compressive Strength

The development of compressive strength with different age such as 7, 14 and 28 days for all mixes was investigated and the result is presented in Figure 4. When MK is added as SCM, there is a significant improvement in the strength of concrete because of high pozzolanic action to form more calcium silicate hydrate (CSH) gel.

And also from the figure, it is clear that the MK admixed mixes attain higher compressive strength values than the control mix which is especially in 10% replacement of MK. The compressive strength development depends upon two parameters i.e., MK replacement level and age of concrete [27–30].

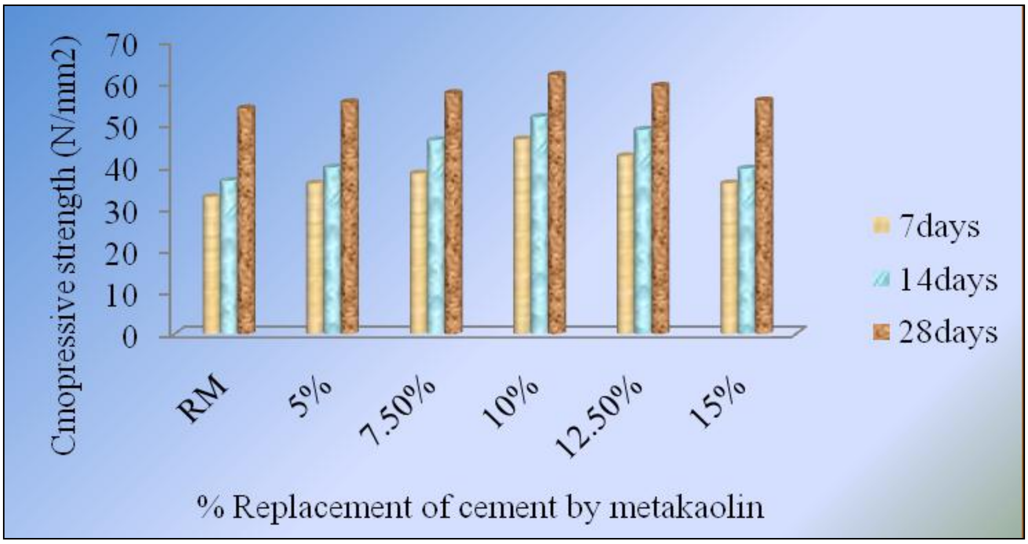

Fig. 4: *Variation of Compressive Strength of Concrete at Different Ages.*

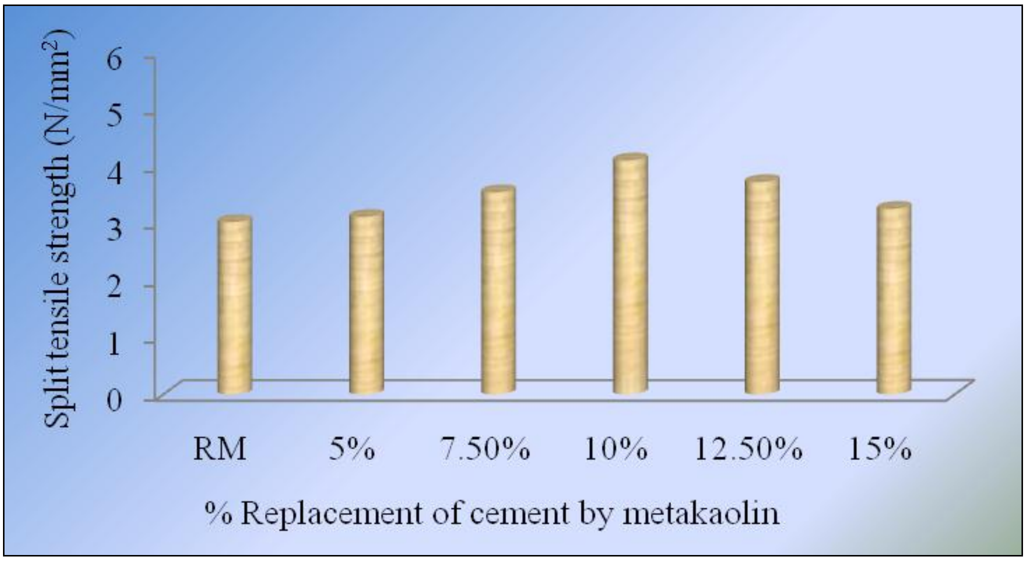

Fig. 5: *Variation of Tensile Strength of Concrete.*

Split Tensile Strength

The tensile strength was compared to control specimen with various percentages of MK at 28 days and these results are illustrated in Figure 5. It shows that the tensile strength of concrete increases with increase in percentage of MK up to 10% replacement level, after that it decreases [28–30]. The tensile strength of concrete at 28 days for different Mixes M2, M3, M4, M5 and M6 a strength gain percentage of 2.98, 17.22, 35.76, 23.18 and 7.62% was obtained respectively when compared with reference mix (M1). The split tensile strength gain is maximum at 10% replacement of cement with MK.

Flexural Strength

The flexural strength was compared to control specimen with various percentages of MK at 28 days and these results are illustrated in Figure 6. It shows that the flexural strength of concrete at 28 days for different mixes such as M2, M3, M4, M5 and M6 a strength gain of 12.90, 37.10, 59.35, 29.03 and 15.48% was obtained respectively when compared with conventional mix (M1) i.e., the value of flexural strength increases from 0% up to 10% of MK addition and then decreases afterwards [28–30]. The maximum value of flexural strength was obtained at 10% replacement of MK.

Durability Test on Concrete

The compressive strength values of specimens subjected to different durability conditions has been shown in Figure 7. From the figure it is understood that, the compressive strength of concrete incorporated with 10% MK is reduced only by 4.09% as compared with no exposure condition during the enhancement of resistance to chloride attack. The compressive strength of concrete incorporated with 10% MK is reduced only by 3.65% as compared with no exposure condition during the enhancement of resistance to sulphate attack [4].

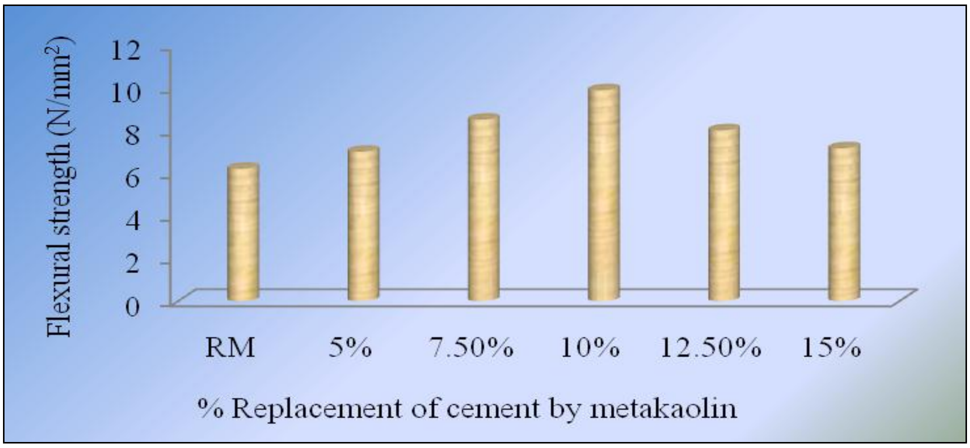

Fig. 6: *Variation of Flexural Strength of Concrete.*

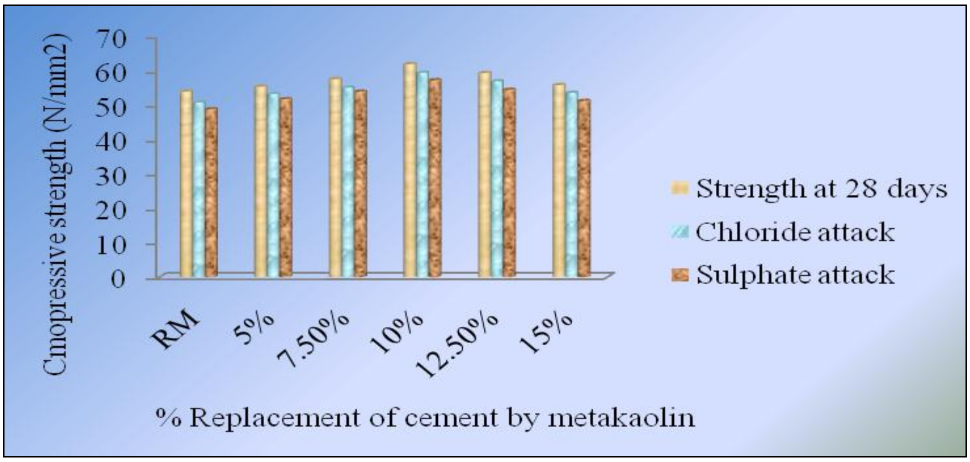

Fig. 7: *Comparison of Compressive Strength Exposed to Different Durability Conditions.*

CONCLUSION

The following conclusions are drawn on the use of MK in concrete making:

- MK reduces the workability of concrete. Also, MK inclusion in concrete improves the mechanical properties of concrete up to 10% replacement level, thereafter the strength is decreasing. In all aspects, concrete with 10% of MK gives better result at all ages.
- Using MK as a partial replacement for cement decreased the density of concrete.
- It can be realized that the HSC and HPC can be developed by utilizing MK and cement designed for a low water/binder ratio of 0.3.
- In MK concrete, the resistance against durability increases for every increment in percentage of MK as compared to reference mix for up to 10% replacement level, and after that it is decreasing.
- The percentage loss of compressive strength and weight are increasing in with the time of exposure to acid attack.
- When compared with cement, the use of MK may be uneconomical due to its high cost whereas it is economical in the aspects of durability and strength.

ACKNOWLEDGEMENT

The authors express their sincere and heartfelt thanks to the Managing Board, Principal, Department of Civil engineering and Department of Chemistry, Mohamed Sathak Engineering College, Kilakarai for providing all research and instrumental facilities. Also, the author expresses sincere thanks to Department of Science and Technology (DST), Science and Engineering Research Board (SERB), New Delhi.

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Cite this Article
Muthumari G, Niraikula Sekaran K. Strength and Durability Properties of Metakaolin Amalgamated High Performance Concrete. *Recent Trends in Civil Engineering & Technology*. 2017; 7(2): 36–44p.