SSRG International Journal of Civil Engineering
ISSN: 2348 – 8352 /doi:10.14445/23488352/IJCE-V6I1P101

Volume 6 Issue 1, 1-6, January 2019

Effect of Metakaolin as a Partial Replacement for Cement on the Compressive Strength of High Strength Concrete at Varying Water/Binder Ratios

Egwuonwu, William, C.#1, Iboroma, Z.S Akobo#2 Barisua E. Ngekpe#3
 # Rivers State University. Portharcourt, Nigeria

Abstract

This research examines the cementitious efficiency of Metakaolin, a supplementary cementitious material (SCM) in high strength concrete production. The mix design was carried out using the Absolute Volume method. The metakaolin was used to replace cement at 2.5%, 5%, 7.5% and 10% at various water/cementitious ratios of 0.20, 0.25, 0.30 and 0.35. The control mix was designed to establish a comparative basis between the mixture blended with Mk and ordinary cement concrete for all mixes. The superplasticizer was also kept constant in all mixes. Water-cementitious ratio and curing ages and the response variables (compressive strengths). The results indicated that the mix design adopted was appropriate for the production of HSC of compressive strength 95.33Mpa.

Keywords — *High Strength Concrete, Metakaolin, Compressive Strength, Absolute Volume Method Water/Binder ratio.*

I. INTRODUCTION

Concrete is extensively used in the construction industry across the world. Every year, an estimated 12 billion tonnes of concrete are used, which comprised approximately 1.6 billion tonnes of Portland cement. The production of cement generates about 5-8% of CO_2 emissions worldwide. Other gases such as SO_3 and Nitrogen oxide are also emitted during cement production, leadingd to or cause the greenhouse effect and acid rain. These lead to severe environmental hazards. Therefore, it is necessary to explore other viable and environmentally friendly cementitious materials for use in the concrete mix. High strength concrete (HSC) could be defined as concrete that meets special performance and uniformity requirements, which is not achievable using only conventional materials and normal mixing, placing, and curing practices. The performance requirement may include ease of placement and compaction without segregation, improved short-term and long-term mechanical properties, high early strength, and long life in an aggressive environment. High strength concrete is achieved using low water to cementitious ratio (w/c). Major physical, mechanical, and durability properties used to characterize high strength concrete under defined conditions.

II. LITERATURE REVIEW

Hamdy et al. (2017) carried out an experimental investigation on high-strength concrete's mechanical behavior made with high percentages of Metakaolin and hybrid fibers with volume fractions of 0.25% and 0.5%. A total of 315 standard test specimens (189 cubes and 126 cylinders) were cast and divided into three groups. Each group consisted of 105 specimens, and each data was based on the average results of 3 test specimens. The Metakaolin (MK) percentage was fixed in all groups (10%, 15%, 20%, 30%, 40%, and 50%) as a percentage of cement weight.

Results revealed that High Strength Concrete (HSC) could be produced with a high volume of Metakaolin. The combined effect of hybrid fiber and Metakaolin showed that MK's optimum dose is 15% at all testing ages. Besides, there was a significant gain in split tensile strength due to Metakaolin and hybrid fiber. Jun et al. (2016) investigated High-Porosity Cement Foams (HPCF) properties based on ternary Portland cement-Metakaolin-Silica fume blends. The effects of ternary blends on the early-age properties of air-void structure and hardened state properties of cement foams were examined.

HPCF slurries were prepared using ordinary Portland Cement, Supplementary Cementitious Materials (SCMs), accelerating agents, superplasticizers (SP), foam agents, and water. Results showed that Metakaolin (MK) and silica fume contributed to stabilizing the air-void structure due to their high pozzolanic activity. Rathan et al. (2013) formulated a simplified mix design procedure for HSC by combining BIS and ACI code methods of mix design. Based on this, a target compressive strength of 60 MPa was obtained.

For the compressive strength test, three cubes were tested for each trial mix combination at the age of 1, 7, 14, 28, and 56 days of curing. It was observed that the strength of concrete blended with metakaolin increases as the incorporation ration of metakaolin increases at all the curing ages. Kasini et al. (2012) studied the influence of Metakaolin (MK) and Calcined Kaolin (CKs) on the compressive strength development of the concrete. The Metakaolin samples investigated were obtained from four different sources in the Czech Republic. Portland cement was replaced with Metakaolin in 5%, 10%, 15%, and 20% for concrete production. A planned mix without admixture was produced for a comparative basis, and compressive strength development of the concrete was evaluated at 3, 7, 28, and 90 days.

It was concluded that Calcined Kaolin incorporated concretes, 15%, was observed to be the optimal replacement level for the concrete compressive strength for 28 and 90 days of curing. Ayman et al. (2015) studied the effect of applying scrap tires in high-strength concrete. Both mechanical and dynamical properties were measured. Two sets of rubberized concrete mixtures were designed and used. The variable slump was used to test the properties of concrete having 0%, 5%, 10%, 15%, 20%, and 30% volume of shredded rubber replacing fine aggregate (sand). The other set was designed to investigate the workability due to variable superplasticizer dosage.

Results revealed that compressive strength reduced as the incorporation ratio of rubber increases. It was also observed that at 15% replacement, compressive strength was not significantly affected.

Ramezanianpour & Bahrami (2012) studied the response of concrete mixtures containing local Metakaolin in terms of compressive strength, water penetration, absorptivity, salt ponding, Rapid Chloride Permeability Test (RCPT), and electrical resistivity subject to 7, 28, 90, and 180 days of curing. Portland cement was replaced with Metakaolin at 0%, 10%, 12.5%, and 15% by mass. Mixes were designed based on w/c ratios of 0.35, 0.4, and 0.5 at a constant binder content of 400 kg/m^3.

The result showed that HSC blended with Metakaolin (MK) show an appreciable increase in compressive over the control mixture (mixture without MK) as the curing age increases. In addition, according to the salt ponding and RCPT tests, it was observed that Metkaolin significantly enhances the resistance to chloride penetration compared with the control mixture. Vahid & Togay (2015) investigated the influence of the addition of steel and polypropylene fibers on the mechanical and durabilities of high-strength concrete (HSC). Hooked and steel fibers were incorporated at volume fractions of 0.25%, 0.50%, 0.75%, and 1.0%. Portland cement was replaced with 10% silica fume. The compressive strength, splitting tensile strength, flexural strength, and water absorption of the concrete mixes were measured.

The experiments' results indicate that the incorporation of silica fume improves both the mechanical and durability properties of plain concrete. The silica fume particles act as a microfilter, thereby, leads to the densification of the transition zone. It was also observed that microsilica has a profound effect on the concrete at later stages of curing. The inclusion of the fiber in the concrete led to the enhancement of mechanical properties for plain concrete. Compressive strength of 82.6 Mpa was measured at 28 days of curing. Hoang et al. (2017) studied the effect of several properties underlying the failure mechanism of high-strength concrete (HSC) under uniaxial compression. An idealized Single Inclusion Block (SIB) was adopted to calibrate the numerical model and calibration of material parameters against experimental data. The model captures the ITZ matrix compressive strength and failure process of the composite SIB correlated well with the experimental results.

Saber & Mahdi (2017) investigated the influences of different amounts of Polypropylene (PP) and Macro-polyphenylene (MP) fibers on the mechanical properties and durability of high-strength concrete containing silica fume and nano-silica. A total of 280 concrete specimens were made and categorized into 28 test groups. The specimens were subjected to compressive strength, tensile strength, elastic modulus, water absorption, and porosity tests.

Results showed that Nano-silica and Silica-fume with the weight percentages of 2 and 12%, respectively. It was also observed that fibers' addition to the concrete mixture and replacement of cement with pozzolan lead to a lower density. The combination of the optimum percentage of the fibers with the pozzolans appreciably enhances most of the Physion mechanical properties of concrete compared with the plain concrete.

Seok-Joon & Hyun-Do (2018) investigated the effects of steel fiber content and coarse aggregate size on high-strength concrete's mechanical properties with a specified compressive strength value of 60MPa. They also studied the correlation between the compressive and flexural toughness of high-strength steel fiber-reinforced concrete (SFRC).

Results showed that both steel fiber volume fraction and aggregate size do not significantly affect the compressive strength and modulus of elasticity of SFRC. Flexural strength, toughness, and the equivalent flexural strength ratio significantly increase fiber content. From the available literature reviewed, there are still divergent views on the optimum dose of Metakaolin as a pleasant replacement material for cement in high strength concrete (HSC). Most researchers observed that the partial replacement of cement with Metakaolin resulted in an appreciable increase in the mechanical and durable properties of high concrete. However, there is a significant dearth of research work on determining the efficiency factor of Metakaolin. The efficiency factor of Metakaolin has been established for self-compacting concrete.

Previous studies confirmed that Metakaolin influences the strength of concrete positively. This indicates that the strength of HSC is principally governed by the water/cement ratios and replacement levels of Metakaolin.

Therefore, this research is tailored towards addressing these gaps. First, control specimens would be prepared at variable water/cementitious ratios of 0.2, 0.25, 0.30, and 0.35 and at partial replacement levels with Metakaolin of 2.5%, 5%, 7.5%, and 10%. Secondly, a comprehensive assessment of the effects of principal variables that influence compressive strength.

Ubojiekere E. Obunwo, et al. (2018). the study investigates Metakaolin's effects on the fresh state and compressive strength of high strength self-compacting concrete. The particle parking model (PPM) was adopted for the mix design of concrete constituents. The prime rationale was to eliminate the void in the self-compacting concrete (SCC). Metakaolin was used to replace cement at three incorporation ratios of 5%, 10%, and 15% at varying water to cementitious ratios of 0.25, 0.30, 0.35, and 0.40. Mixes were designed to achieve both self-compatibility and high compressive strength. Several workability tests such as slump flow, L- box, V-funnel, and J-ring were carried out. The compressive strength was measured at 7, 14, and 28 days of wet curing. The results showed that the mix design method was adequate to the proportion of SCC mixtures containing cement and Metakaolin. All fresh state properties satisfied EFNARC criteria (EFNARC, 2005). The highest compressive strength of 69.6 MPa was obtained for concrete using Metakaolin. For all mixtures, Metakaolin increased compressive strength appreciably. A similar trend was observed in all the concrete mixes, and there was a progressive increase in compressive strength as the metakaolin inclusion level increased.

III. MATERIALS AND METHODS

The following materials were used in the experimental design;

- Ordinary Portland cement manufactured by Dangote Cement Company (Conforming to EN 196 – 1:1987)
  Source: COREN, 2017
- Natural fine sand aggregates of 5mm maximum size conforming (conforming to BS 882:1992).
- Natural granite aggregates of maximum size (20mm) from crushed rock industries in Port Harcourt.
- Portable water from the university mains conforming to BS 3148 (1970).
- Metakaolin
- Superplasticizer dosage (SP), a polycarboxylate ether PCE based super plasticizer was used. Based on the manufacturer's prescription, the dosage level should be between 1% to 1.3% of the total cementitious or powder content of superplasticizer conforming to EN 934 – 2 was used in this study.

The sample preparation, fresh and hardened state tests were carried out in the structural laboratory, department of Civil Engineering, Rivers State University.

IV. MIX DESIGN PROCEDURE

Mix design can be defined as the combination of optimum proportions of the constituent materials to fulfill the requirements of fresh and hardened concrete for a specific application for HSC; achievement of high strength is the prime target of the mix design. The Absolute volume method Mix design procedure was adopted in accordance with BS8110.
Assumed a suitable water/cement ratio and determined the target strength based on the curing age as presented below.

- Determination of the free water-cementitious ratio: It can be obtained directly from the chart in Figure 1. The curve shows an inverse relationship between mean compressive strength and the water/cement ratio at different ages.

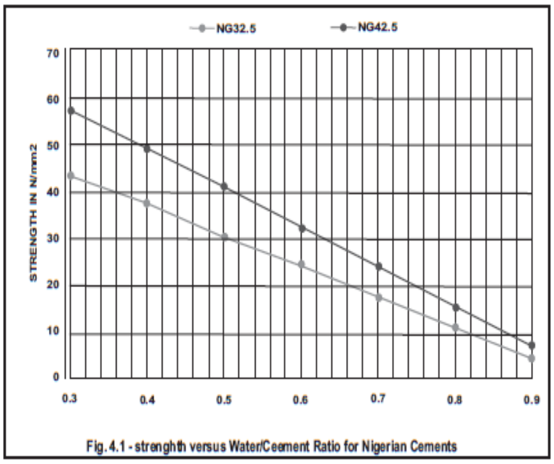

Figure 1: Compressive Strength-Water/Cement Ratio Curve

Alternatively, the empirical relationship of Equation 1 provided by (Lydon 2002) can be used to compute the compressive strength at a specified water/cement ratio.

$$f_c = \frac{140.44}{(10.92)^{w/c}}$$

- Water content is obtained from the table below based on the expected slump value. For strength, the water content is lower than 180 kg/m^3.

Table 1: Summary of the Mix Ratio for this Research

Mix	Percentage replacement (%)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Course aggregate (kg/m^3)	Metakaolin (kg/m^3)	Water (kg/m^3)	Superplasticizer (% of Cement)
0.2	0	620	645.98	984.47	0	124	1.2
	2.5	604.5	645.98	984.47	15.5	124	1.2
	5	589	645.98	984.47	31.0	124	1.2
	7.5	573.5	645.98	984.47	46.50	124	1.2
	10	558	645.98	984.47	62.0	124	1.2
0.25	0	496	687.07	1047.06	0	124	1.2
	2.5	483.60	687.05	1047.06	12.40	124	1.2
	5	471.20	687.05	1047.06	24.80	124	1.2
	7.5	458.8	687.05	1047.06	37.20	124	1.2
	10	446.4	687.05	1047.06	49.60	124	1.2
0.3	0	413.33	715.32	1090.15	0	124	1.2
	2.5	403	715.32	1090.15	10.33	124	1.2
	5	392.67	715.32	1090.15	20.66	124	1.2
	7.5	382.33	715.32	1090.15	30.99	124	1.2
	10	372	715	1090.15	41.33	124	1.2
0.35	0	354.29	734.46	1119.32	0	124	1.2
	2.5	345.45	734.46	1119.32	8.86	124	1.2
	5	336.58	734.46	1119.32	17.71	124	1.2
	7.5	327.72	734.46	1119.32	26.57	124	1.2
	10	318.86	734.46	1119.32	35.43	124	1.2

V. RESULTS AND DISCUSSION

A. *Compressive Strength*

The test results of cube compressive strength for all mixtures at 7, 14, and 28 days are presented in Table 2 below. The variation in compressive strength for a specimen containing Metakaolin (MK) and Metakaolin inclusion levels is plotted at various curing ages. From Table 2, it is observed that the concrete sample exhibits the highest compressive strength value of 95.33 MPa with 0.20 water-cement ratio and 10% replacement of cement with Metakaolin.

Table 2: Compressive Strength Result for Concrete Mixtures under Different Curing Ages.

Water-cement ratio	% Replacement of cement with Metakaolin (%)	Compressive Strengths (MPa)		
		7 days	14 days	28 days
0.2	0.0	64.67	71.00	82.07
	2.5	79	81.67	89
	5.0	80	83.33	91
	7.5	81.5	84.67	92.67
	10	83.33	88.67	95.33
0.25	0.0	58.67	67.50	73.44
	2.5	66	69.67	79
	5.0	70	72.67	78
	7.5	72.67	78	82.67
	10	75.33	77.33	85.33
0.30	0.0	40.43	49.07	61.56
	2.5	43.33	54.67	54.66
	5.0	44.67	57.83	73.33
	7.5	46	54.73	77
	10	48.33	55.33	70.67
0.35	0.0	37.82	47.51	58.67
	2.5	39.33	51.33	65

	5.0	44.67	52.33	68
	7.5	46	54.33	70
	10	47.33	55.23	73

At 7 days curing age, it was observed that the compressive strength increased on increasing inclusion level of Metakaolin. At w/c of 0.20, the highest increase in compressive strength of 28.85% was observed at 10% Metakaolin inclusion level. Appreciable enhancement of about 22.16%, 23.7%, 26.02% was observed compared to the control specimen at Metakaolin content of 2.5%, 5%, and 7.5%, respectively. At w/c of 0.25, appreciable or significant enhancement of about 12.49%, 19.31%, 23.86% and 28.40% were observed compared to the control specimen at Metakaolin content of 2.5%, 5%, 7.5% and 10% respectively. At w/c of 0.30, significant enhancement of about 9.89%, 13.29%, 16.66% and 22.57% was observed compared to the control specimen at Metakaolin content of 2.5%, 5%, 7.5% and 10% respectively. Also, at w/c ratio of 0.35, significant enhancement of about 4%, 18.11%, 21.63% and 25.15% were observed compared to control specimen at Metakaolin content of 2.5%, 5%, 7.5% and 10% respectively.

Based on these results, it can be concluded that Metakaolin content exhibited the most significant effect at a water-cement ratio (w/c) of 0.20. Also, it can be concluded that Metakaolin contributed significantly to compressive strength at an early age.

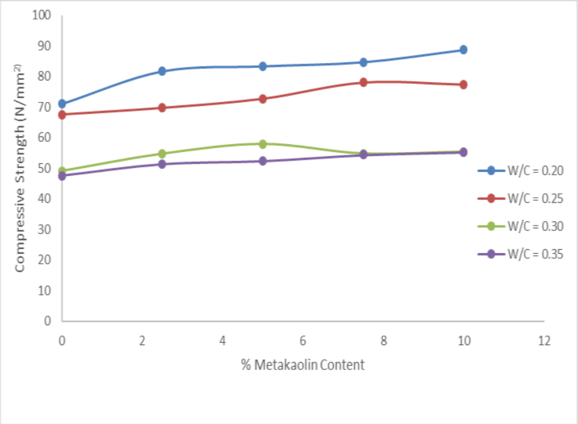

Figure 2: Graph of Compressive Strengths of Samples after 7 Days Curing

At 14 days curing age, it was observed that the compressive strength increased on increasing inclusion level of Metakaolin. At w/c of 0.20, the highest increase in compressive strength of 24.89% was observed at 10% Metakaolin inclusion level. Appreciable enhancement of about 15.03%, 17.37%, 19.25% was observed compared to the control specimen at Metakaolin content of 2.5%, 5%, and 7.5%, respectively. At w/c of 0.25, appreciable or significant enhancement of about 3.22%, 7.66%, 15.56% and 14.56% were observed compared to the control specimen at Metakaolin content of 2.5%, 5%, 7.5% and 10% respectively. At w/c of 0.30, significant enhancement of about 11.41%, 17.85%, 11.53% and 12.76% was observed compared to the control specimen at Metakaolin content of 2.5%, 5%, 7.5% and 10% respectively. Also, at w/c ratio of 0.35, significant enhancement of about 8.04%, 10.15%, 14.36% and 16.25% were observed compared to control specimen at Metakaolin content of 2.5%, 5%, 7.5% and 10% respectively.

Based on these results, it can be concluded that Metakaolin content exhibited the most significant effect at a water-cement ratio (w/c) of 0.20.

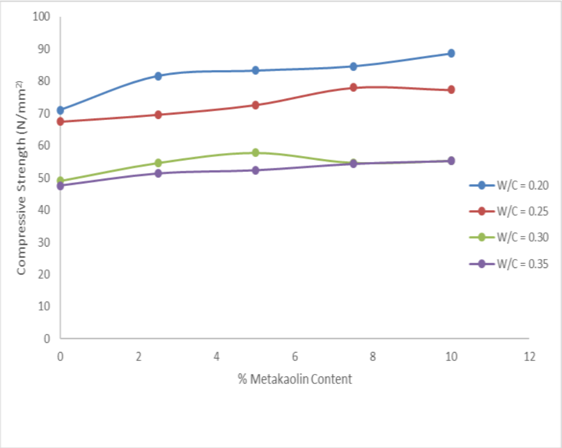

Figure 3: Graph of Compressive Strengths of Samples after 14 Days.

At 28 days curing age, it was observed that the compressive strength increased on increasing inclusion level of Metakaolin. At w/c of 0.20, the highest increase in compressive strength of 16.17% was observed at 10% Metakaolin inclusion level. Appreciable enhancement of about 8.44%, 10.88%, 12.92% was observed compared to the control specimen at Metakaolin content of 2.5%, 5%, and 7.5%, respectively. At w/c of 0.25, appreciable or significant enhancement of about 7.57%, 6.21%, 12.57% and 16.19% were observed compared to the control specimen at Metakaolin content of 2.5%, 5%, 7.5% and 10% respectively. At w/c of 0.30, significant enhancement of about -11.21%, 19.20%, 25.08% and 14.80% was observed compared to the control specimen at Metakaolin content of 2.5%, 5%, 7.5% and 10% respectively. Also, at w/c ratio of 0.35, significant enhancement of about 10.79%, 15.90%, 19.31% and 24.42% were observed compared to control specimen at Metakaolin content of 2.5%, 5%, 7.5% and 10% respectively.

Based on these results, it can be concluded that Metakaolin content exhibited the most significant effect at a water-cement ratio (w/c) of 0.30.

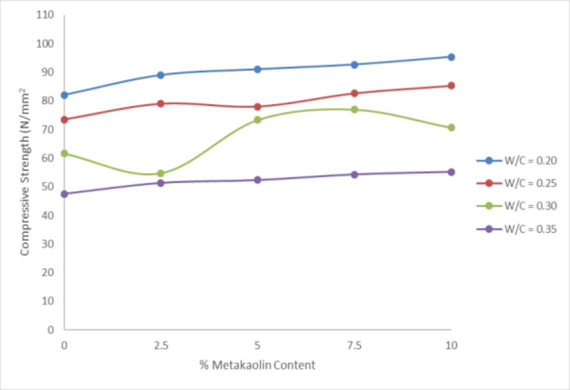

Figure 4: Graph of Compressive Strengths after 28 Days Curing

VI. FINDINGS AND CONCLUSION

This research aimed to develop an improved mix design method for high strength concrete (HSC). Metakaolin's cementitious efficiency was explored as a partial replacement material for cement in the production of HSC. The functional relationship between the input variables (concrete constituents and curing age) is examined in detail. Based on the experimental and analytical results, the following conclusions can be drawn;

- The mix design method (AVM) provides a satisfactory result for both fresh and hardened state properties. Therefore, this mixed design procedure can be applied for high-end structural applications.

- At 10% replacement of cement with Metakaolin at 0.2 water-cement ratios, the maximum value of compressive strength (95.33 MPa) was measured at 28 days of water curing. Therefore, a 10% replacement can be recommended for practical applications. A similar observation has been reported in the literature.

- To establish a comparative basis, the increase in strength compared to the control mix, Metakaolin was observed to increase the compressive strength by 28.85% at 10% replacement level at 7 days curing. This progressive increment in strength as the curing age increases could be traceable to the significant reduction of voids, which improves the degree of hydration and the microstructural characteristics of the HSC.

- In the range of 2.5 – 10 wt % cement replacement, Metakaolin was very effective in improving the compressive strength of HSC. Therefore, the underlying design of the HSC could be successfully based on the proposed value range of the efficiency factor for Metakaolin.

REFERENCES

[1] Ayman, M., & Mohamed, A. E., Mechanical Properties of High Strength Concrete with Scrap Tire Rubber. Journal of Construction and Building Materials, 93, (2015),249-256.

[2] Hamdy, K., Shehab. E., Ahmed, S., Eisa, B. H., Abdel, A., & Ahmed,I., Mechanical Performance of High Strength Concrete Made from High Volume of Metakaolin and Hybrid Fibers. Journal of Construction and Building Materials.,140, (2017),203-209.

[3] Jun, J., Zhongyuan, L., Yun, H. N., Jun, L., & Yu, P. Z., Investigation of the Properties of High-Porosity Cement Foams Based on Ternary Portland Cement-Metakaolin-Silica Fume Blends. Journals of Construction and Building Materials. 107, (2016),181-190.

[4] Malhotra, V. M, & Metha, P. K.,High Performance, High Volume Fly Ash Concrete, Supplementary Cementing Materials for Sustainable Development. (2nd Edition). Ottawa: ONT, (2005).

[5] Ubojiekere, E.O, Barisua, E.N, Godfrey, W.G.J, Chimene, O., Workability and Mechanical Properties of High-strength Self-Compacting Concrete blended with Metakaolin. International Journal of Civil Engineering., 5, (2018),2348 – 8352

[6] Ramezanicanpour, A. A., & Bahrami, J. H., Influence of Metakaolin as Supplementary Cementing Material on Strength and Durability of Concretes. Journal of Construction and Building Materials. ,30, (2012), 470-479.

[7] Rangan, B. V., High-Performance High-Strength Concrete: Design Recommendations. Concrete Inter., (1998).

[8] Rathan, R., Perumal, P. E. B. & Santhakumar, A. R., Evaluation and Mix Design for Ternary Blended High Strength Concrete. Chemical, Civil, and Mechanical Engineering Tracks of 3rd Nirma University International Conference (NuiCONE 2012). Procedia Engineering.,51, (2013),65-74.

[9] Saber, F., & Mahdi, N., Mechanical Properties and Durability of High-Strength Concrete Containing Macro-Polymeric and Polypropylene Fibers with Nano-Silica Fume. Journal of Construction and Building Materials, 132, (2017), 170-187.

[10] Scrivena, K. I, & Kirkpatrick, R., Innovation in Use and Research on Cementitious Material. In: 12th International Congress of Chemistry of Cement, Montreal, Canada;(2007).

[11] Seok-Joon, J., & Hyun-Do, Y., Combined Effects of Steel Fiber and Coarse Aggregate Size on the Compressive and Flexural Toughness of High-Strength Concrete. Journal of Composite Structures, 185, (2018),203-211.

[12] Topçu, B., & Sarıdemir, M,. Prediction of Compressive Strength of Concrete Containing Fly Ash Using Artificial Neural Network and Fuzz Logic. Comput. Mater. Sci. 41(3), (2008),305-311.

[13] Vahid, A. F. & Togayozba, L,. Mechanical and Durability Properties of High-Strength Concrete Containing Steel and Polypropylene Fibers. Journal of Construction and Building Materials, 94, (2015),73-82.