

Studies on Workability and Strength Aspects of OPC - MK - RM Based Ternary Blended Concrete

R. Rathan Raj¹, E.B. Perumal Pillai², A.R.Santhakumar³

¹Assistant Professor, Department of Civil Engineering, Sathyabama University, Chennai – 600 119, India.

²Professor & Principal, R M K College of Engineering and Technology, Puduvoyal – 601 206, Thiruvallur District, Tamilnadu, India.

³Professor & Consultant, CDMM, College of Engineering, Guindy, Anna University, Chennai – 600 025, India.

Abstract:- In this study the physical and mechanical properties of concrete of Ordinary Portland Cement (OPC) containing metakaolin (MK) or redmud (RM) and a combination of MK and RM and compatibility between such materials were investigated on different mixture proportions of water/binder ratio (w/b) 0.38, 0.36 and 0.33 by replacing 0% to 14% of the mass of cement by MK and RM with different proportions of 50:50, 60:40, 70:30 and 80:20. The workability of concrete was measured by the slump, compaction factor and Vee-Bee consistometer tests. Substantial reductions in the workability were obtained for the mixtures containing MK and RM, with greater reductions being experienced as the RM replacement level increased. The cube compressive strength was evaluated at 1, 7, 14, 28 and 56 days for all w/b ratios. It is found that the maximum compressive strengths are obtained with 8% replacement of OPC by MK, 4% replacement of OPC by RM and 10% replacement of OPC by MK and RM blend in all w/b ratios. In all the w/b ratios the MK:RM Proportions of 80:20 achieve higher strength.

Keywords:- Metakaolin, Redmud, Workability, Strength, ternary blend

I. INTRODUCTION

Ordinary Portland Cement (OPC) is recognized as the major construction material throughout the world [1]. Industrial wastes, such as blast furnace slag, fly ash and silica fume are being used as supplementary cementitious materials. In addition to this, agricultural wastes such as rice husk ash, wheat straw ash and bagasse ash are also being used as pozzolanic materials. When pozzolanic materials are added to cement, the silica (SiO₂) present in these materials reacts with free lime released by the hydration of cement and forms additional silicate hydrate (CSH) as new hydration products [2], which improve the mechanical properties of the concrete formulation.

Metakaolin (MK) is an artificial pozzolana produced by burning selected kaolinite clay within a specific temperature range (between 650 °C and 800 °C). The production process is closely controlled and thus higher purity and reactivity can be obtained. MK is basically made up of silica and alumina in an amorphous state, that react with calcium hydroxide (CH) produced by Portland cement hydration to form calcium hydrosilicate (C-S-H) and calcium hydroaluminosilicate (essentially gehlenite – C₂ASH₈) [3]. Metakaolin, because of its white color, does not darken concrete, making it suitable for color matching and other architectural applications.

Redmud (RM) is a by-product of the Bayer process, which is used for the production of alumina from bauxite. For each part of alumina produced by this process, about one part of redmud is generally discarded as a waste. India generates over 4 million tones of this by-product annually which is not otherwise put to any use. Over the years, many attempts have been made to find a use for redmud, but none have proven to be economically satisfactory. These attempts were based mainly on the use of redmud as a partial substitute for clay in the production of bricks and other ceramics products [4], [5]. Redmud has a reddish-brown colour and a superfine, fine particle-size distribution as it's physical characteristics, as well as alkalis, iron oxides and hydroxides, aluminium hydroxides, calcium carbonate, titania and silica in its chemical composition. This superfine particle characteristic of redmud makes this a promising admixture for mortar and concrete [6]. The redmud is fairly caustic, with pH of pastes being typically in the range 11-13. Except for the residual NaOH left after the final washing in the plant, the components of redmud are usually considered to be relatively inert and unreactive[7]. Despite its apparent inertness and obvious lack of reactive silica, the idea of utilizing the pozzolanic reaction to bind redmud mixtures seemed to be a feasible and potentially low cost alternative for the very simple reason that the redmud is a high pH environment. The admixtures required would be hydrated lime,

either with fly ash, bagasse ash, silica fume, granulated blast furnace slag or metakaolin; and all of these are readily available, or can be produced. A further possibility for production of cementitious compounds that hydrated lime will react with the alumina left in redmud to produce calcium aluminates (CA possibly C_5A_3). These also hydrate to produce cementitious components, in reactions which are fairly well known from the fact that they are responsible for the strengths of high alumina cement mortars [8]. The reaction of lime with alumina is considered to be a type of pozzolanic reaction as well.

This paper reports on a study to evaluate optimum percentage level of MK and RM separately and with combinations to the cement replacement. The aim of the work is to determine the compressive strength at all stages of curing and for the range of water/binder (w/b) ratios.

II. EXPERIMENTAL PROCEDURES

A. Materials and Mix Proportion

The following materials were used: Ordinary Portland Cement (OPC) 53 grade (specific gravity: 3.15, Blaine fineness: $320 \text{ m}^2/\text{Kg}$), Metakaolin (MK) (specific gravity: 2.54, Blaine fineness: $15 \text{ m}^2 / \text{gm}$), Redmud (RM) (specific gravity: 2.74, Blaine fineness: $10.5 \text{ m}^2 / \text{gm}$), Fine Aggregate (FA) (specific gravity: 2.60, fineness modulus: 2.964), Course Aggregate (CA) (specific gravity: 2.82, fineness modulus: 6.73) and Sulfonated naphthalene formaldehyde condensate based superplasticizer conplast SP 430 (specific gravity: 1.220). The chemical composition of Ordinary Portland Cement (OPC), Metakaolin (MK) and Redmud (RM) are presented in the Table 1.

Table 1: Chemical Composition of OPC, MK and RM

Type	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	SO ₃	MgO	Na ₂ O	K ₂ O	Ig-loss
OPC	21.8	4.8	3.8	63.3	2.2	0.9	0.21	0.46	2.0
MK	52.3	44.9	0.4	0.5	<0.1	0.2	0.12	0.02	0.8
RM	9.91	20.8	49.0	1.92	0.21	<0.01	4.11	<0.01	11.50

A concrete mix proportion of water/binder ratios 0.38, 0.36 and 0.33 with characteristic target mean compressive strength of 40 Mpa, 50 Mpa and 60 MPa is designed without any mineral admixtures. However, the use of several trial mixes is important in the design of concrete. Therefore, to get the optimum proportions, trial mixes were arrived by replacing 0, 2, 4, 6, 8, 10, 12 and 14 percent of the mass of cement by MK and RM in the proportions of 50:50, 60:40, 70:30 and 80:20 respectively. A total of 30 trial mixes of different combinations were arrived for each w/b ratio. In all the above combinations, a superplasticizer (SP) was used at 1% by weight of the binder for obtaining workable concrete. Trial mixes were carried out to achieve the required workability range for the different mixture compositions. The cement, metakaolin and redmud were thoroughly blended together by hand until a uniform colour was achieved. The superplasticizer, where used, was mixed with the water before adding to the dry ingredients. Mixing is done in the room temperature of $25 \pm 3^\circ\text{C}$. The compositions of the three binder components and mixture details for the concrete with w/b 0.38, 0.36 and 0.33 are given in Tables 2 - 4.

B. Measurement of Workability

Workability was measured by the slump, the compaction factor and the Vee-Bee degree tests in compliance with BIS: 7320 – 1974, BIS: 5515 – 1983 and BIS: 10510 – 1983 respectively. The slump test is simple to carry out and is useful for measuring consistency and detecting variations in uniformity. The compacting factor test measures the ease by which fresh concrete is compacted. In addition the degree of compaction determined by the density ratio in the compacting factor test, gives a relative measure of the void content of concrete. The Vee-Bee consistometer test determines the time needed to achieve full compaction of the concrete under standard vibration. This test is appropriate, therefore for the concretes with low w/b ratios and high admixture contents like metakaolin and redmud examined in this study. The workability measurements were carried out immediately after mixing, all three tests being completed within 20 minutes.

C. Specimen Preparation and Curing

The compressive strength was determined from the average of test results for three standard 150 mm cubes prepared in steel moulds. The sampling was carried out in accordance with BIS: 1199 - 1959. Each mould was kept in room temperature to preserve the initial moisture condition of the sample, after 24 hours, the samples were demoulded and cured in the water at $20 \pm 1^\circ\text{C}$, until testing. The compressive strength tests were carried out in a 400 Tonne capacity compression testing machine as per BIS: 516-1959. The tests were carried out at a uniform stress after the specimen has been centered in the testing machine.

Table 2: Mix Proportions, w/b = 0.38

Mix	Replacement %	% Ratio	Cement Kg	MK Kg	RM Kg	FA Kg	CA Kg	SP Liters	Water Liters	
CC	0 %	--	381.58	--	--	895.51	1044.91	7.83	144.12	
MK ₂	2%	--	373.95	7.63	--	893.87	1044.91	7.83	144.12	
RM ₂			373.95	--	7.63	894.05	1044.91	7.83	144.12	
MK ₄	4%	--	366.32	15.26	--	892.23	1044.91	7.83	144.12	
RM ₄			366.32	--	15.26	892.60	1044.91	7.83	144.12	
MK ₆	6%	--	358.69	22.90	--	890.58	1044.91	7.83	144.12	
RM ₆			358.69	--	22.90	891.14	1044.91	7.83	144.12	
MR _{6A}			50:50	358.69	11.45	11.45	890.86	1044.91	7.83	144.12
MR _{6B}			60:40	358.69	13.74	9.16	890.81	1044.91	7.83	144.12
MR _{6C}			70:30	358.69	16.03	6.87	890.75	1044.91	7.83	144.12
MR _{6D}			80:20	358.69	18.32	4.58	890.69	1044.91	7.83	144.12
MK ₈	8%	--	351.05	30.53	--	888.95	1044.91	7.83	144.12	
RM ₈			351.05	--	30.53	889.70	1044.91	7.83	144.12	
MR _{8A}			50:50	351.05	15.26	15.26	889.34	1044.91	7.83	144.12
MR _{8B}			60:40	351.05	18.32	12.21	889.25	1044.91	7.83	144.12
MR _{8C}			70:30	351.05	21.37	9.16	889.18	1044.91	7.83	144.12
MR _{8D}			80:20	351.05	24.42	6.11	889.10	1044.91	7.83	144.12
MK ₁₀	10%	--	343.42	38.16	--	887.32	1044.91	7.83	144.12	
RM ₁₀			343.42	--	38.16	888.25	1044.91	7.83	144.12	
MR _{10A}			50:50	343.42	19.08	19.08	887.78	1044.91	7.83	144.12
MR _{10B}			60:40	343.42	22.89	15.26	887.70	1044.91	7.83	144.12
MR _{10C}			70:30	343.42	26.71	11.45	887.60	1044.91	7.83	144.12
MR _{10D}			80:20	343.42	30.53	7.63	887.50	1044.91	7.83	144.12
MK ₁₂	12%	--	335.79	45.79	--	885.68	1044.91	7.83	144.12	
RM ₁₂			335.79	--	45.79	886.79	1044.91	7.83	144.12	
MR _{12A}			50:50	335.79	22.89	22.89	886.25	1044.91	7.83	144.12
MR _{12B}			60:40	335.79	27.47	18.32	886.13	1044.91	7.83	144.12
MR _{12C}			70:30	335.79	32.05	13.74	886.01	1044.91	7.83	144.12
MR _{12D}			80:20	335.79	36.63	9.16	885.90	1044.91	7.83	144.12
MK ₁₄	14%	--	328.16	53.42	--	884.04	1044.91	7.83	144.12	
RM ₁₄			328.16	--	53.42	885.34	1044.91	7.83	144.12	

Table 3: Mix Proportions, w/b = 0.36

Mix	Replacement %	% Ratio	Cement Kg	MK Kg	RM Kg	FA Kg	CA Kg	SP Liters	Water Liters	
CC	0 %	--	402.78	--	--	877.71	1044.91	8.26	143.80	
MK ₂	2%	--	394.72	8.06	--	875.98	1044.91	8.26	143.80	
RM ₂			394.72	--	8.06	876.17	1044.91	8.26	143.80	
MK ₄	4%	--	386.87	16.11	--	874.08	1044.91	8.26	143.80	
RM ₄			386.87	--	16.11	874.48	1044.91	8.26	143.80	
MK ₆	6%	--	378.61	24.17	--	872.52	1044.91	8.26	143.80	
RM ₆			378.61	--	24.17	873.11	1044.91	8.26	143.80	
MR _{6A}			50:50	378.61	12.08	12.08	872.82	1044.91	8.26	143.80
MR _{6B}			60:40	378.61	14.50	9.67	872.75	1044.91	8.26	143.80
MR _{6C}			70:30	378.61	16.92	7.25	872.69	1044.91	8.26	143.80
MR _{6D}			80:20	378.61	19.33	4.83	872.65	1044.91	8.26	143.80
MK ₈	8%	--	370.56	32.22	--	870.79	1044.91	8.26	143.80	
RM ₈			370.56	--	32.22	871.58	1044.91	8.26	143.80	
MR _{8A}			50:50	370.56	16.11	16.11	871.18	1044.91	8.26	143.80
MR _{8B}			60:40	370.56	19.33	12.89	871.10	1044.91	8.26	143.80
MR _{8C}			70:30	370.56	22.56	9.67	871.02	1044.91	8.26	143.80
MR _{8D}			80:20	370.56	25.78	6.44	870.95	1044.91	8.26	143.80
MK ₁₀	10%	--	362.50	40.28	--	869.06	1044.91	8.26	143.80	
RM ₁₀			362.50	--	40.28	870.04	1044.91	8.26	143.80	
MR _{10A}			50:50	362.50	20.14	20.14	869.55	1044.91	8.26	143.80
MR _{10B}			60:40	362.50	24.17	16.11	869.45	1044.91	8.26	143.80
MR _{10C}			70:30	362.50	28.19	12.08	869.37	1044.91	8.26	143.80
MR _{10D}			80:20	362.50	32.22	8.06	869.26	1044.91	8.26	143.80
MK ₁₂	12%	--	354.45	48.33	--	867.33	1044.91	8.26	143.80	
RM ₁₂			354.45	--	48.33	868.51	1044.91	8.26	143.80	
MR _{12A}			50:50	354.45	24.17	24.17	867.91	1044.91	8.26	143.80
MR _{12B}			60:40	354.45	28.99	19.33	867.81	1044.91	8.26	143.80
MR _{12C}			70:30	354.45	33.83	14.50	867.69	1044.91	8.26	143.80
MR _{12D}			80:20	354.45	38.66	9.67	867.57	1044.91	8.26	143.80
MK ₁₄	14%	--	346.39	56.39	--	865.60	1044.91	8.26	143.80	
RM ₁₄			346.39	--	56.39	866.98	1044.91	8.26	143.80	

III. RESULTS AND DISCUSSIONS

The mixtures containing metakaolin and redmud with w/b ratio 0.38 and 0.36 exhibit measurable slumps in the range 10-70. In w/b ratio 0.33, due to increased percentage of replacement of metakaolin and redmud, there is no slump. It is noted that the particles of metakaolin and redmud disperse amongst the cement, block the capillary channels, thus little free water can raise to the surface of the fresh concrete because of the efficient packing. The increased percentage replacement of binder results in more paste volume, which also contributes to a reduction in bleeding. The concretes behaved in a cohesive and mobile manner during the compacting factor and Vee-Bee degree tests. It is to be pointed out that all the mixtures used in this work exhibited slumps less than 100 mm which is considered as low. The production of high strength concrete is usually accompanied by the use of superplasticizers which would result in more flowable concrete.

Table 4: Mix Proportions, w/b = 0.33

Mix	Replacement %	% Ratio	Cement Kg	MK Kg	RM Kg	FA Kg	CA Kg	SP Liters	Water Liters
CC	0%	--	439.39	--	--	846.98	1044.91	8.99	143.26
MK ₂	2%	--	430.60	8.79	--	845.09	1044.91	8.99	143.26
RM ₂			430.60	--	8.79	845.31	1044.91	8.99	143.26
MK ₄	4%	--	421.81	17.58	--	843.21	1044.91	8.99	143.26
RM ₄			421.81	--	17.58	843.63	1044.91	8.99	143.26
MK ₆	6%	--	413.03	26.36	--	841.32	1044.91	8.99	143.26
RM ₆			413.03	--	26.36	841.96	1044.91	8.99	143.26
MR _{6A}		50:50	413.03	13.18	13.18	841.64	1044.91	8.99	143.26
MR _{6B}		60:40	413.03	15.82	10.55	841.57	1044.91	8.99	143.26
MR _{6C}		70:30	413.03	18.45	7.91	841.51	1044.91	8.99	143.26
MR _{6D}		80:20	413.03	21.09	5.27	841.45	1044.91	8.99	143.26
MK ₈	8%	--	404.24	35.15	--	839.43	1044.91	8.99	143.26
RM ₈			404.24	--	35.15	840.29	1044.91	8.99	143.26
MR _{8A}		50:50	404.24	17.58	17.58	839.85	1044.91	8.99	143.26
MR _{8B}		60:40	404.24	21.09	14.06	839.78	1044.91	8.99	143.26
MR _{8C}		70:30	404.24	24.61	10.55	839.68	1044.91	8.99	143.26
MR _{8D}		80:20	404.24	28.12	7.03	839.61	1044.91	8.99	143.26
MK ₁₀	10%	--	395.45	43.94	--	837.55	1044.91	8.99	143.26
RM ₁₀			395.45	--	43.94	838.62	1044.91	8.99	143.26
MR _{10A}		50:50	395.45	21.97	21.97	838.08	1044.91	8.99	143.26
MR _{10B}		60:40	395.45	26.36	17.58	837.98	1044.91	8.99	143.26
MR _{10C}		70:30	395.45	30.76	13.18	837.87	1044.91	8.99	143.26
MR _{10D}		80:20	395.45	35.15	8.79	837.76	1044.91	8.99	143.26
MK ₁₂	12%	--	386.66	52.73	--	835.66	1044.91	8.99	143.26
RM ₁₂			386.66	--	52.73	836.95	1044.91	8.99	143.26
MR _{12A}		50:50	386.66	26.36	26.36	836.31	1044.91	8.99	143.26
MR _{12B}		60:40	386.66	31.63	21.09	836.19	1044.91	8.99	143.26
MR _{12C}		70:30	386.66	36.90	15.82	836.06	1044.91	8.99	143.26
MR _{12D}		80:20	386.66	42.18	10.54	835.93	1044.91	8.99	143.26
MK ₁₄	14%	--	377.88	61.52	--	833.77	1044.91	8.99	143.26
RM ₁₄			377.88	--	61.52	835.27	1044.91	8.99	143.26

A. Workability Effects Caused by Metakaolin

Figure 1 shows the variations in slump, compacting factor and Vee-Bee degree with increasing metakaolin contents in concrete. It is seen that for all w/b ratios (0.38, 0.36 and 0.33) the workability parameters decrease systematically with the increased replacement level of metakaolin and greater reductions being observed for the concretes with higher w/b ratio. For the mixture with w/b ratio 0.33 compared to the Control Concrete (CC) shows a drop of nearly 40 mm of slump, decrease the value of compaction factor by nearly 0.1 and increase in Vee-Bee degree by 25 seconds, when 14 % of ordinary Portland cement is replaced by metakaolin. Whereas for w/b ratio 0.38 shows a drop of nearly 50 mm of slump, decrease the value of compacting factor by nearly 0.070 and increase in Vee-Bee degree by 22 seconds. The workability reductions produced by metakaolin addition in concrete is due to its high specific surface area ($15 \text{ m}^2/\text{gm}$), which leads to more water being absorbed. There is also a function of high chemical reactivity, which results in greater consumption of water during cement hydration. These combined effect results in an increase in water demand. Increasing the w/b ratio in concrete resulted in considerable reduction in workability even though a superplasticizer was used.

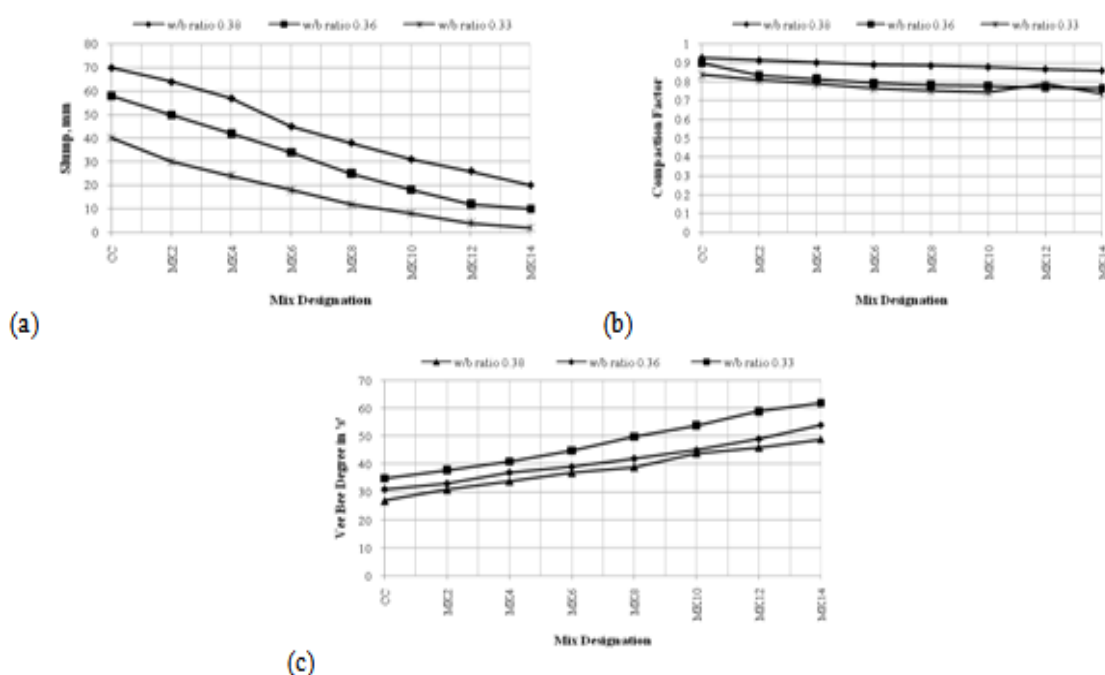


Fig.1: Influence of MK on Workability of Concrete (a) Slump Value (b) Compaction Factor and (c) Vee-Bee Degree

B. Workability Effects Caused by Redmud

Figure 2 shows the variations in slump, compacting factor and Vee-Bee degree with increasing redmud additions in the concrete. There is no slump in w/b ratio 0.33, at increased percentage of replacement of RM by 10%. There is a considerable reduction in the compaction factor value nearly by 0.1 in w/b ratio 0.33, and an increased value of the Vee-Bee degree by 38 seconds compared to the control concrete when 14 % of OPC is replaced by redmud.

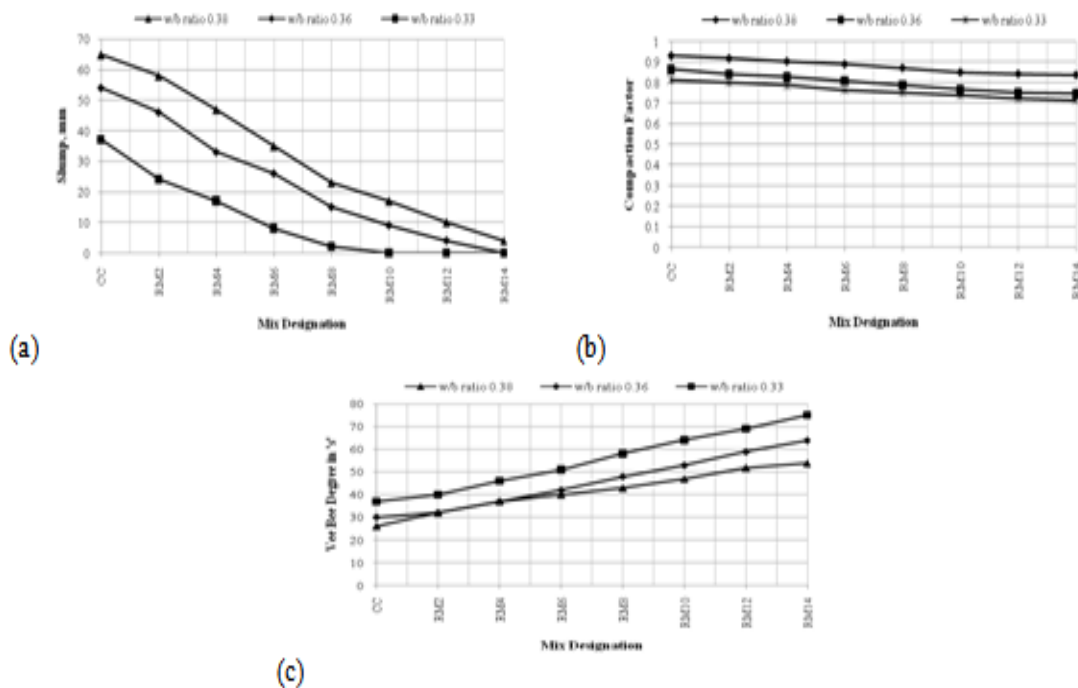


Fig. 2: Influence of RM on Workability of Concrete (a) Slump Value (b) Compaction Factor and (c) Vee-Bee Degree

Whereas for w/b ratio 0.38 shows a drop of nearly 60 mm of slump, decrease the value of compacting factor by nearly 0.090 and increase in Vee-Bee degree by 28 seconds. The decrease in slump, compacting factor

and increase in Vee-Bee degree may be attributed to the fineness and water absorbing characteristics of redmud. The decrease in slump, compacting factor and increase in Vee-Bee degree is more for higher w/b ratios because for the same volume of concrete the quantity of redmud is more.

C. Effects of Metakaolin on Cube Compression

For cube compression testing of concrete, 150mm cubes were employed. All the cubes were tested in saturated condition, after wiping out the surface moisture. For each trial mix combination, three cubes were tested at the age of 1, 7, 14, 28 and 56 days of curing using 400 Tonne capacity compression testing machine as per BIS: 516-1959. The tests were carried out at a uniform stress after the specimen has been centered in the testing machine. The variations in the strength of concrete with increasing replacement level of ordinary Portland cement by metakaolin at the three w/b ratios are shown in Figure 3.

The strength of metakaolin concrete increase systematically with an increase in metakaolin level at all three w/b ratios and at all curing times. The maximum compressive strengths are obtained for mixes with 8% replacement of ordinary Portland cement by metakaolin in all w/b ratios. That is, as the metakaolin content increases from 0% the compressive strength gradually increases up to metakaolin content reaches 8% and thereafter, it gradually falls off. This is due to the fact that the compressive strength increases in concrete due to the pozzolanic reaction and filler effect of the metakaolin.

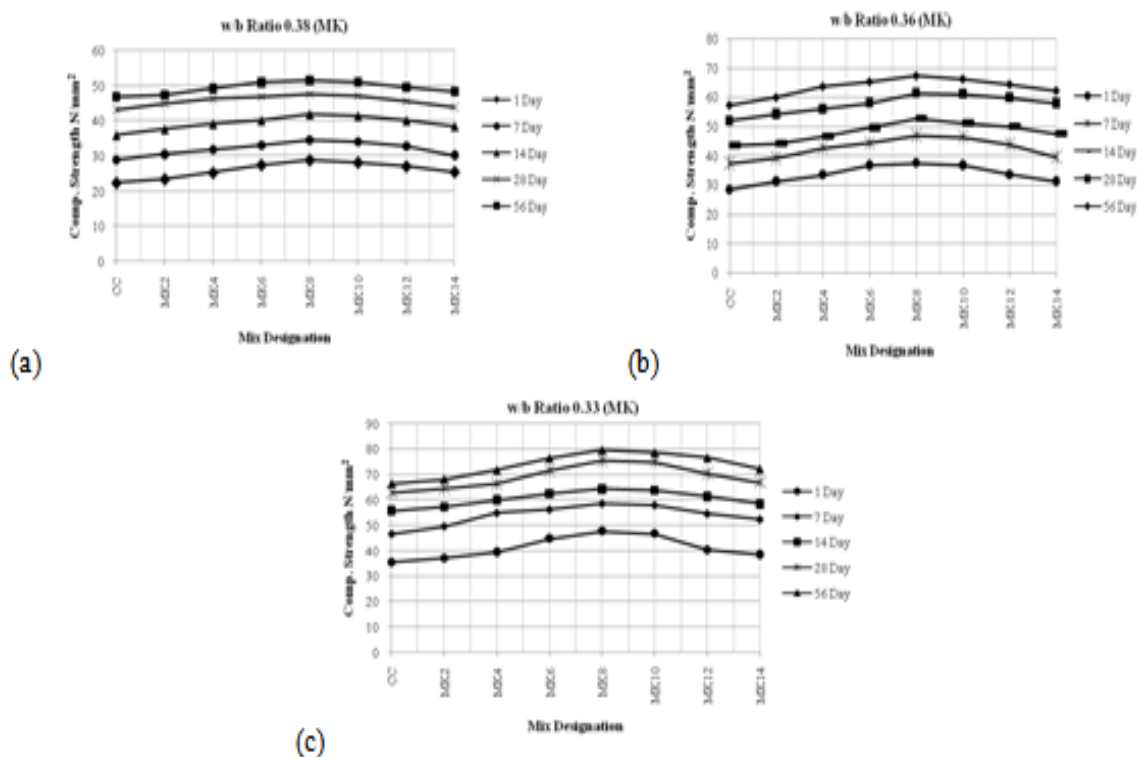


Fig. 3: Influence of MK on Cube Strength of Concrete (a) w/b Ratio 0.38, (b) w/b Ratio 0.36 and (c) w/b Ratio 0.33

In the pozzolanic reaction, the metakaolin reacts with calcium hydroxide (which is a hydration product of cement) and produces more C-S-H gel. C-S-H gel is the source of strength of hardened concrete, as it is the binder which binds the aggregate together. If the metakaolin percentage in the concrete is increased gradually, it reaches a point called an optimum point, where its content is exactly what is required for reacting with the calcium hydroxide present. Excess metakaolin added beyond this limit will remain in free form as there won't be any calcium hydroxide to react with. Free metakaolin in concrete does not act as a binder, and hence will cause a reduction in strength. The 7 days to 28 days compressive strength ratio of 10% replacement for w/b ratio 0.38, 0.36 and 0.33 are 0.727, 0.766 and 0.773 respectively; whereas for the control concrete of same w/b ratios are 0.669, 0.719 and 0.743. It is noted that this compressive strength ratio is increased with increase in w/b ratio. Also the rate of increase in compressive strength is higher compared with the controlled concrete.

D. Effects of Redmud on Cube Compression

Figure 4 shows the influence of the level of ordinary Portland cement replacement by redmud on the compressive strength of concrete at ages 1, 7, 14, 28 and 56 days for the three w/b ratios employed. As might be expected, systematic reductions in strength are observed at all ages as the w/b ratio is increased. It is evident from these figures that the strength increases up to 4 % replacement of redmud in all three w/b ratios. However beyond 4 % the strength starts decreasing for all mixes. The increase in strength may be due to the fact that the cement replacement of around 4 % increases the finer particles in the mix, which increase its density by filling the voids and hence the compressive strength. Another reason for increase in strength may be due to extra availability of Al_2O_3 , SiO_2 and TiO_2 whose presence up to certain percentage increases the strength of concrete by combining with other constituents of cement during the progress of hydration. The 7 days to 28 days compressive strength ratio of 4% replacement for w/b ratio 0.38, 0.36 and 0.33 are 0.758, 0.788 and 0.823 respectively: whereas for the control concrete of same w/b ratios are 0.669, 0.719 and 0.743. It is noted that this ratio is increased with increase in w/b ratio; also the 7 day strengths of redmud replacements are high compared to the concrete replacement of metakaolin. This is due to the presence of alumina contents resulting in the early strength development.

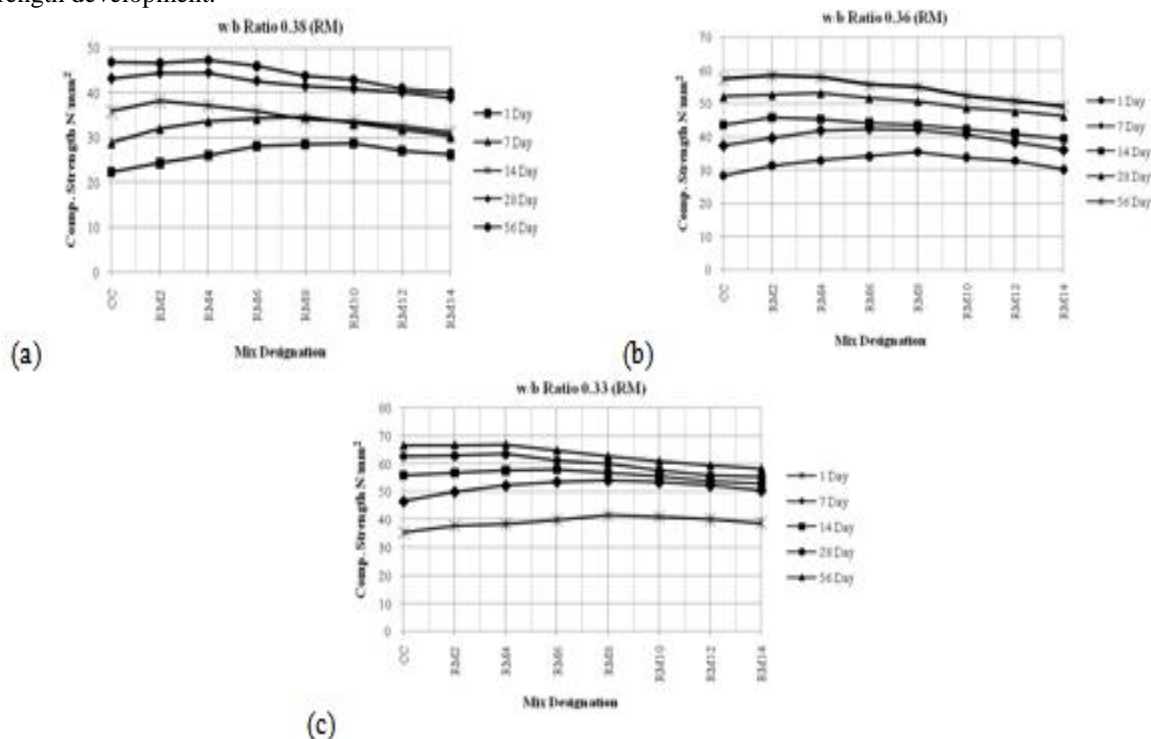


Fig. 4: Influence of RM on Cube Strength of Concrete (a) w/b Ratio 0.38, (b) w/b Ratio 0.36 and (c) w/b Ratio 0.33

E. Effects of Metakaolin and Redmud Blend on Cube Compression

Figure 5 shows, for the three w/b ratios of 1, 7, 14, 28 and 56 day strengths of concrete containing various metakaolin and redmud blends as partial ordinary Portland cement replacement. The graph represents different total percentage of replacement levels (6%, 8%, 10% and 12%) with the different metakaolin:redmud (MK:RM) proportions (50:50, 60:40, 70:30 and 80:20). In general the strength increases with metakaolin content of the blend increases and the strength decreases as RM content of the blend increases. In all the w/b ratios at 10% of total replacement, where a maximum in strength occurs at 80% metakaolin and 20% redmud. This is discussed previously, possibly associated with acceleration of the hydration reactions.

A good indication of the effectiveness of the various blend compositions is to compare them with the strengths of the control concretes at the same ages. In all the replacement levels and of different MK:RM proportions the variations of the strengths are very small, the 12 % replacement level shows similar values of the control concrete. Beyond the 10% replacement levels there are remarkable reductions in the strength; it shows that 10% replacement is acting as the optimum replacement level which gave higher strengths. In the w/b ratio 0.38, at the 10% replacement level the compressive strength of MK:RM proportion 50:50 and 80:20 are 7.1% and 7.5% higher than the control concrete, the w/b ratio 0.36, at the 10% replacement level the compressive strength of MK:RM proportion 50:50 and 80:20 are 8.6% and 9.1% higher than the control concrete and In the w/b ratio 0.33, at the 10% replacement level the compressive strength of MK:RM proportion 50:50 and 80:20

are 6.2% and 6.7% higher than the control concrete. It was noted that a small increase in compressive strength is only due to the pozzolanic effect of metakaolin alone; the redmud particles are acting as a filler materials in concrete, and this phenomena was same for all the mixes in three w/b ratio.

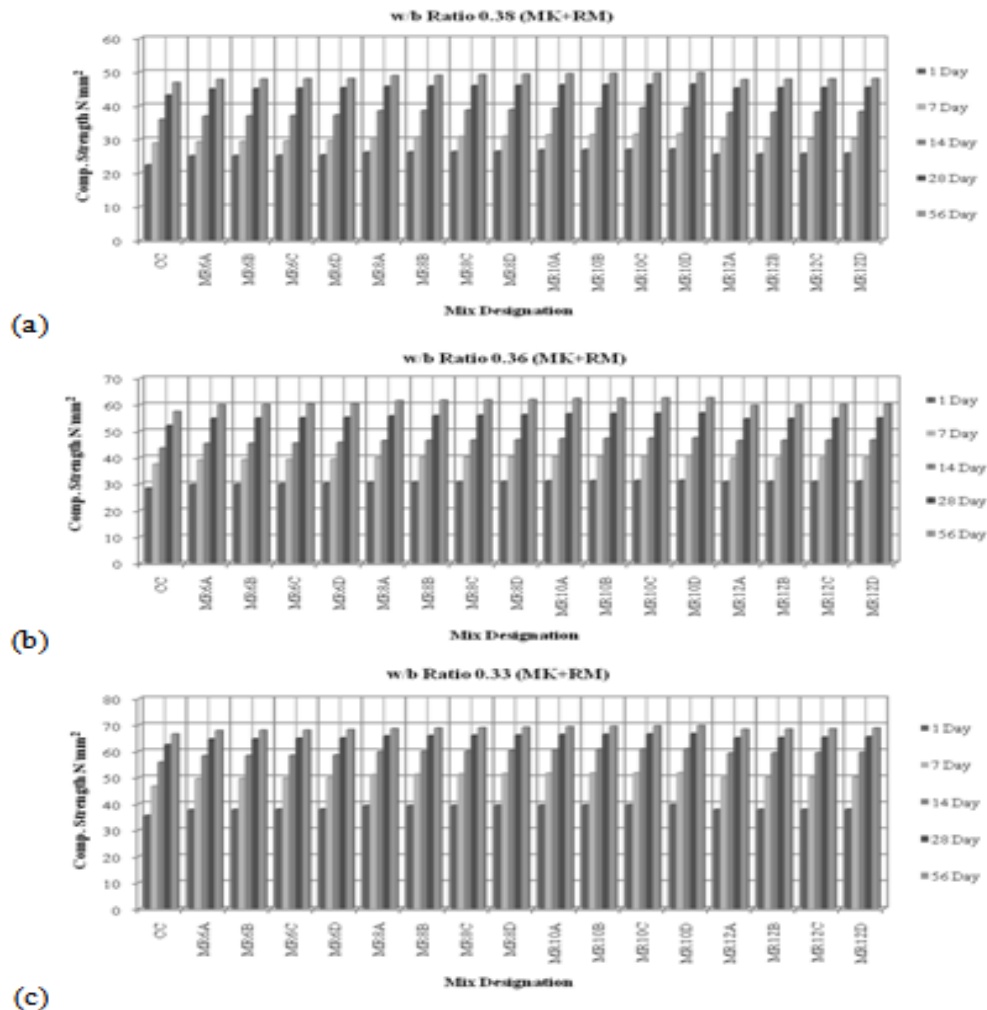


Fig. 5: Influence of MK-RM blend Compositions on Cube Strength of Concrete (a) w/b Ratio 0.38, (b) w/b Ratio 0.36 and (c) w/b Ratio 0.33

IV. CONCLUSIONS

The following conclusions may be drawn from the work presented in this paper.

- From the present study, the optimum percentage of replacement of metakaolin with ordinary Portland cement for highest compressive strength in concrete at all curing time for all the w/b ratios used (0.38, 0.36 and 0.33) is 8%.
- Due to its high pozzolanic reactivity, metakaolin resulted in a higher rate of compressive strength development upto 28 days curing thereafter the strength development decreased.
- For w/b ratios 0.38, 0.36 and 0.33 the percentage increase in strength at 28 days curing period at 8% replacement of metakaolin by ordinary Portland cement compared with controlled concrete are 10.35%, 17.83% and 20.37%, whereas at 56 days curing period the corresponding values are 10.17%, 17.62% and 19.69%
- The workability in terms of slump of concrete with metakaolin at 8% replacement compared with controlled concrete is reduced by 45.71%, 56.9% and 70% of w/b ratios 0.38, 0.36 and 0.33.
- The workability reduction caused by metakaolin is attributed to its high chemical activity and high specific surface area, resulting in increased water uptake and hence greater water requirement.
- The optimum replacement of redmud with ordinary Portland cement for highest compressive strength of concrete at 28 days curing for all the w/b ratios used (0.38, 0.36 and 0.33) is 4%.
- The percentage increase of early compressive strength of concrete (7 day curing period) with redmud at 4% replacement compared with controlled concrete is 16.86%, 12.00% and 12.17% for w/b ratio of 0.38, 0.36 and 0.33, whereas at 28 days curing the percentage increased by 3.11%, 2.09% and 1.18%.

- viii. In the early age strength development, the pozzolanic action developed due to extra availability of Al_2O_3 , SiO_2 and TiO_2 . The 28 day compressive strength beyond 4% replacement level is decreased in all w/b ratios.
- ix. The workability in terms of slump of concrete with redmud at 4% replacement compared with controlled concrete of w/b ratios 0.38, 0.36 and 0.33 is reduced by 27.69%, 38.88% and 54.05%.
- x. The workability of concrete with redmud is severely reduced with the increase in replacement of redmud content. For the higher grade of concrete with the higher replacement levels the slump is nearly zero. The decrease in slump, compaction factor and increase in Vee-Bee degree by RM replacement is attributed to the fineness and high water absorbing characteristics of redmud particles.
- xi. In the strength development of metakaolin and redmud blends as partial replacement of ordinary Portland cement, the strength increases with increase in metakaolin content of the blend and the strength decreases with increase in redmud content of blend. In all the w/b ratios of MK:RM proportion 80:20 achieves the greatest strength. For all the replacement levels and for different MK:RM proportions, the strength variations are insignificant.
- xii. In all the w/b ratios with all MK:RM proportions replacement, the small increase in compressive strength is due to pozzolanic and acceleration of hydration reactions of MK alone.

The results presented in this paper are the basis for the selection of OPC-MK-RM blended cements for concrete in order to satisfy workability and strength criteria. Durability properties are also important in deciding the overall long term performance of concrete. The durability characteristics of these materials are presently being assessed in a separate study.

ACKNOWLEDGMENT

The authors gratefully acknowledge and wish to thank the English Indian Clay Limited, Trivandram and the Madras Aluminium Co.Ltd (MALCO), Mettur for providing metakaolin and redmud required for this investigation.

REFERENCES

- [1]. Bentur, A., (2002) "Cementitious materials – Nine millennia and a new century: Past, Present and Future", ASCE Journal of Materials in Civil Engineering, vol. 14(1) pp.1-22.
- [2]. Boating, A.A. and Skeete D.H., (1990), "Incineration of rice hull for use as a cementitious materials: The Guyana experience", Cement and Concrete Research, vol 20 pp.795-802.
- [3]. Jian-Tong, D. and Zongjin L., (2002) "Effects of metakaolin and silicafume on properties of concrete", ACI Materials Journal, vol. 99, pp. 393-398.
- [4]. Amritphale, S.S. And Patel, M., (1987) "Utilization of redmud, flyash for manufacturing bricks with pyrophyllite", Silic. Ind., vol.31, pp. 3-4.
- [5]. San Filippo, A. and Usai, G., (1998) "Recycling of redmud from the Bayer process. Part. 2. Production of vertified clayware at a firing temperature of over 1000° C", Ziegelind. Int., vol. 4, pp. 133.
- [6]. Khono, K., Amo, K., Ogawa, Y. and Ikezoe, Y., (1993) "Effect of admixture consisting of finally ground silica and redmud on properties of high strength concrete for products", Proceedings of the 4th EASEC, Seoul, Korea, vol. I, pp. 1437.
- [7]. Junior, N. Gordon, Willard R. Pinnock, and Marcia M. Moore, (1996) "A Preliminary Investigation of strength development in Jamaican Redmud Composites", Cement and Concrete Composites, vol. 18, pp. 371-379.
- [8]. Majumdar, A.J., Singh, B. and Edmonds, R.N., (1990) "Hydration of mixtures of 'cement fondu', aluminous cement and granulated blast furnace slag", Cement and Concrete Research, vol. 20, pp. 197-208.
- [9]. Sabir, B.B., (1995) "High strength condensed silica fume concrete", Magazine of Concrete Research, vol. 47, No. 172, pp. 219-226.
- [10]. Vu, D.D., Stroeven. P. and Bui, V.B., (2001) "Strength and durability aspects of calcined kaolin-blended Portland cement mortar and concrete", Cement and Concrete Composites, vol. 23, pp. 471-478.
- [11]. Bai, J., Wild, S. and Sabir, B.B., (1999) "Workability of concrete incorporating pulverized fuel ash and metakaolin", Magazine of Concrete Research, vol. 51(3), pp. 207-216.
- [12]. Brooks, J.J, Johari, M.A.M. and Mazloom, M., (1994) "Effects of admixtures on the setting time of high strength concrete", Cement and Concrete Composites, vol. 22(1), pp. 293-301.
- [13]. Caldaron, M.A., Gruber, K.A. and Burg, R.G., (1994) "High reactivity metakaolin (HRM): a new generation admixture for high performance concrete", Concrete International, vol. 16(11), pp. 37-40.
- [14]. Curcio, F., Deangelis, B.A. and Pagliolico S., (1998) "Metakaolin as pozzolanic micro filler for high performance mortars", Cement and Concrete Research, vol. 28(6), pp. 800-809.

- [15]. Ding, J.T. and Li, Z. J., (2002) "Effects of metakaolin and silica fume in properties of concrete", *ACI Materials Journal*, vol. 99(4), pp. 393-398.
- [16]. Kohno, K., Amo, y., Ogawa, y. and Gyatoku, M., (1995) "Properties of Mortar and concrete using Red Mud and Finely Ground Silica", *ACI SP*, 153-58, pp. 1103-1120.
- [17]. Pera, J. and Momtazi A.S., (1992) "Pozzolanic Activity of Calcined Red Mud", *ACI SP* 132-41, pp. 749-761.
- [18]. Kumar, K., Nautiyal, B.D. and Jha, A.K., (1989) "Use of Neutralized Red Mud in Concrete", *Indian Concrete Journal*, pp. 505-507
- [19]. Majumdar, A.J. and Singh, B., (1992) "Properties of some high alumina cements", *Cement and Concrete Research*, vol. 22, pp. 1101-1114.
- [20]. Pinnock, Willard, R., Junior, N. Gordon and Moore, M., (1997) "A preliminary investigation of strength development in Jamaican red mud composites", *Cement and Concrete Composites*, vol. 18, pp.371-379.
- [21]. Zhihua pan, Lin Cheng, Yinong Lu, and Nanru Yang, (2002) "Hydration products of alkali-activated slag-red mud cementitious material", *Cement and Concrete Research*, vol. 32, pp. 357-362.
- [22]. Zhihua pan, Li Dongxu, Jian Yu and Yang Nanru, (2003) "Properties and microstructure of hardened alkali-activated slag-red mud cementitious material", *Cement and Concrete Research*, vol. 33, pp. 1437-1441.
- [23]. Chunming Gong, and Nanru Yang, (2000) "Effect of phosphate on the hydration of alkali-activated red mud-slag cementitious material", *Cement and Concrete Research*, vol. 30, pp. 1013-1016.
- [24]. Pera, J., Boumaza, R. and Ambroise, J., (1997) "Development of a pozzolanic pigment from red mud", *Cement and Concrete Research*, vol. 27(10), pp. 1513-1522.
- [25]. Singh M., Upadhyay S.N. and Prasad P.M., (1997) "Preparation of iron rich cements using red mud", *Cement and Concrete Research*, vol. 27(7), pp. 1037-1046.
- [26]. Indian standard code of practice for Plain and reinforced Concrete for general building construction IS: 456-2000. Bureau of Indian Standards, New Delhi.
- [27]. Indian standard code of practice for Specification for coarse and fine aggregates from natural sources for concrete, (2nd revision) IS: 383-1970. Bureau of Indian Standards, New Delhi.
- [28]. Indian standard code of practice for Methods of test for strength of concrete, IS: 516-1959. Bureau of Indian Standards, New Delhi.
- [29]. Indian standard code of practice for Methods of test for aggregates for concrete", specific gravity, density, voids, absorption and bulking, IS: 2386 (part3)-1963. Bureau of Indian Standards, New Delhi.
- [30]. Indian standard code of practice Specification for Admixtures for Concrete", (1st revision), IS: 9103-1999. Bureau of Indian Standards, New Delhi.
- [31]. Indian standard code of practice for Specification for 53 grade ordinary Portland cement, IS: 12269-1987. Bureau of Indian Standards, New Delhi.
- [32]. Indian standard code of practice for Methods of sampling and analysis of concrete, IS: 1199 – 1959. Bureau of Indian Standards, New Delhi.
- [33]. Indian standard code of practice for Specification for Concrete Slump test apparatus, IS: 7320-1974. Bureau of Indian Standards, New Delhi.
- [34]. Indian standard code of practice for Specification for Compaction factor apparatus, IS: 5545-1983. Bureau of Indian Standards New Delhi.
- [35]. Indian standard code of practice for Specification for Vee-Bee consistometer, IS: 10510-1984. Bureau of Indian Standards, New Delhi.