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Technical Paper

Study on effect of fly ash and limestone powder on compressive strength of roller compacted concrete for dam construction

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Abstract: Roller compacted concrete (RCC) is a special concrete having similar ingredients as in the case of conventional concrete, but in different proportions. Use of fly ash to replace significant proportion of Portland cement (PC) for RCC mix is very popular. However, use of limestone in RCC is not so popular. Limestone can act as an inert filler as well as can take part in hydration process and development of different hydration products to a limited extent. The study attempts to determine the optimal replacement levels of PC using fly ash and limestone for development of high volume fly ash based roller compact concrete with limestone filler for use in construction of dams in India by evaluating the fresh properties (in terms of Vee Bee time, density and setting time) and compressive strength (at 7, 28, 56, 90 and 180 days) for different RCC mixes having varying proportions of PC, fly ash and limestone. The study evaluation of 17 RCC mixes prepared by replacing PC to an extent of 72% (by weight of total cementitious content) using two types of fly ash and two types of limestone from different sources to observe the variations in setting time, short and long-term strength for the concrete. For RCC mixes having ternary cementitious systems (combination of OPC, fly ash and limestone), setting time values were observed to be in between setting times of mixes made with binary cementitious systems (i.e. OPC and limestone & OPC and fly ash). Optimum performance in terms of compressive strength at all the ages was observed for mixes with ternary cementitious system due to the synergistic contributions (physical and chemical) of both fly ash and limestone.

Keywords: Roller Compacted Concrete, Mass Concrete, Fly ash, Limestone Powder, Compressive Strength.

1. Introduction

Roller compacted concrete (RCC) is a stiff, zero-slump concrete mixture. It is prepared in the form of a dry concrete and is further transported by dump trucks to the construction site, laid in layers by grader or similar construction equipment and compacted by vibratory rollers [1]. To make it suitable for compaction using vibratory rollers, RCC in its fresh state shall be dry enough to resist the weight of roller during compaction and prevent its sinking and also shall be wet enough to remain cohesive and get compacted by the vibrations [2]. Cementitious materials, water along with coarse and fine aggregates of RCC mix are mixed in a certain proportion (based on various trials) to make a zero-slump heterogeneous mix which has consistency similar to that of a damp gravel. Along with being economical in terms of cost, use of RCC leads to increase in speed of construction at site, very little use of formwork during construction and reduces the carbon footprint by substitution of cement with supplementary cementitious materials [3].

It is used in different applications such as heavy-duty mass concrete structures at ports, dam construction along with roadway and paving applications [4]. Construction of dams constructed using RCC costs significantly less in comparison to construction of dams using conventional concrete [5]. RCC can be cast and compacted in different layers which leads to significantly better dissipation of heat generated during hydration of cement in mass concrete, preventing thermal stresses induced cracks. RCC has been used for construction of major dam structures across the globe such as the “Willow Creek Dam” in United States (constructed in 1982), the “Longtan Dam” in China (constructed in 2009) and the “Gilgel Gibe III Dam” in Ethiopia (constructed in 2015) [3]. RCC exhibits similar degree of

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mechanical strength and other concrete related properties [6] in comparison to those of conventional concrete [7-11]. Similar to conventional concrete, mechanical properties of Roller Compacted Concrete can also be improved by use of steel fibers[12,13]. The major difference between RCC and conventional concrete primarily lies in the proportion of the individual concrete constituents. Around 70-80 % percent of the total volume of an RCC mix is comprised of aggregates. Apart from aggregates and water, other major constituent includes cementitious binder which can be made up of only Ordinary Portland cement or a combination of Portland cement (PC), fly ash, limestone or ground granulated blast furnace slag. Chemical admixtures in the form of retarders can be used in appropriate concentration to enhance the setting time of RCC mix. Fine aggregates in RCC mix is higher in comparison to conventional concrete mix which improves overall packing and consolidation of mix [14]. Initial consistency of a RCC mix is evaluated using Vee Bee method unlike slump cone test used in case of conventional concrete.

Production of clinker for conventional PC leads to significant emission of greenhouse gas and thereby contributes to almost 10% of anthropogenic emission of carbon dioxide across the world. Reduction of cement content and replacing it with suitable proportion of supplementary cementitious materials in total binder content for making concrete is very important in releasing some environmental pressures occurring due to construction industry [15]. In view of above, research work is being carried out for development of RCC using a combination of cement and fly ash or cement, fly ash and limestone. Literature suggests that combination of fly ash with limestone for replacing PC in total binder creates a synergistic effect which compensates for their individual shortcomings as binder [16, 17]. Several research studies [17, 21] revealed that concrete made with ternary cement blend (combination of limestone, PC and fly ash in appropriate proportion) leads to development of higher compressive strength in comparison to concrete made with binary cement blend (combination of PC and fly ash only).

Fresh and hardened properties of RCC mix can be modified by using mineral admixtures such as fly ash as replacement of PC in total binder. Fly ash comprises of reactive aluminates and silicates and can contribute to the behaviour of the overall mix through its morphologic, pozzolanic and micro aggregate characteristics [22]. The pozzolanic behaviour of fly ash comes into picture when SiO_2 and Al_2O_3 present in fly ash are activated by portlandite (i.e. $Ca(OH)_2$), in the presence of water, resulting in development of additional hydration product similar to C-S-H gel which leads to gain in strength at later ages. Research studies [23] on strength development of RCC using high proportion of fly ash in cementitious binder i.e. high volume fly ash roller compacted concrete (HFRCC) revealed that HFRCC mix has lower strength at early ages and the role of fly ash at early age is almost negligible. However, with increase in age of HFRCC mix, strength development rate gets faster as role/effect of fly ash comes in picture and the effect of fly ash on strength of HFRCC mix gets stronger at a longer ages of curing with increase in quantity of fly ash. Research studies [24] on heat of hydration and temperature control of HFRCC to be used for mass concrete structures such as dams suggest that since Roller Compacted Concrete contains higher proportion of fly ash in total cementitious binder, increase in adiabatic temperature of RCC mix is lower because the significant proportion of fly ash in cementitious binder would lead to delay in dissipation of heat of hydration.

However, the decline of coal as a power source due to the increasing popularity of renewable energy and cleaner forms of fuels may lead to decrease in supply of fly ash in future. Hence, it is imperative to look for other possible alternative materials which can be used to replace PC content in cement. Limestone is can act as an inert filler as well as can take part in hydration process and development of different hydration products to a limited extent. The extent of involvement of limestone in chemical hydration reactions depends on the fineness of limestone. Studies conducted by Matschei et al [25] showed that carbonates present in limestone reacts with aluminates present in cementitious binder to form different carboaluminate phases. The extent of reaction of limestone is controlled by concentration of sulphate ions in pore solution. With increase in sulphate concentration, increase in unreacted calcite present is observed. Use of fly ash and limestone together as replacement of PC in total cementitious binder can lead to improvement in the pore structure of hardened concrete during hydration of cement, when mean particle sizes of fly ash and limestone are smaller than that of PC [26, 27].

The objective of this study is to determine the optimal replacement levels of PC using fly ash and limestone for development of high volume fly ash based roller compact concrete with limestone filler without negatively affecting its fresh properties and compressive strength at different ages.

2. Experimental Program

Selection of materials for RCC mix is governed by various factors, but some of the important factors which influences the material selection is the strength requirement, workability and type of application. Like standard concrete, the materials required to produce RCC are cementitious materials, water, aggregates and admixtures. The cementitious materials used in the present study were Ordinary Portland cement (OPC) satisfying IS 269: 2015 [28], fly ash conforming to IS 3812 (Pt-1): 2003 [29] and classification of limestone powder used in the study has been done based on CaO criteria suggested by Panda et al. [30] and MgO criteria suggested by Ramaiah et al [31]. Physical and chemical characteristics of OPC and fly ash samples used in the study have been tabulated in Table 1 and Table 2 respectively. Two sources of fly ash designated as FA 1 & FA 2 and two source of lime stone designated as LS1 & LS2 from eastern part of India were used in the study. The setting time of concrete with admixture was evaluated by varying the doses of retarding chemical admixture with control mix as per IS 1199 (Pt-7): 2018 [32]. Limestone used in the study in case of both the sources are high grade / high calcium limestone as evident from results given in Table-3 and compared with criteria given in Table 4 and Table 5.

The coarse aggregate with size in range of 4.75 mm to 40 mm were used for RCC mixes. These aggregates were differentiated into three size groups A40 (20-40mm), A20 (10-20mm) and A10 (4.75-10mm). The specific gravity of the aggregates is about 2.7 and water absorption lies between 0.4 and 0.6.

Table -1. Physical and chemical characteristics of OPC

S. No.	Properties	Results Obtained	IS Code Specifications IS 269: 2015
PHYSICAL TEST			
1	Blain’s fineness, m^2/kg	317	More than 225
2	Setting time, minutes Initial Final	 125 185	 More than 30 Less than 600
3	Compressive strength, N/mm^2 3 days 7 days 28 days	 33.5 44.0 54.0	 More than 23 More than 33 Between 43 and 58
4	Specific Gravity	3.13	3.15 for OPC
CHEMICAL TEST			
1	Loss on Ignition (% by mass)	4.43	Less than 5
ss 2	Magnesium Oxide (% by mass)	3.55	Less than 6
3	Sulphuric Anhydride (% by mass)	2.66	Less than 6
4	Insoluble Residue (% by mass)	2.16	Less than 5
5	Chloride (% by mass)	0.012	Less than 0.1
6	Alkali (% by mass) Sodium Oxide Potassium Oxide Eq. as Na_2O	 0.02 0.40 0.28	Eq. Na_2O shall be less than 0.6 percent
7	Silica (% by mass)	19.69	Ratio of percentage of lime to percentage of silica, alumina and iron oxide when calculated by equation-1 shall be between 0.66 to 1.02. For cement selected for study value is 0.94. Equation-1 $(CaO-0.7SO_3)/(2.8SiO_2+1.2Al_2O_3+0.65Fe_2O_3)$
8	Iron Oxide (% by mass)	3.52	
9	Alumina (% by mass)	4.49	
10	Calcium Oxide (% by mass)	60.91	

Table - 2 Physical and chemical characteristics of fly ash samples

S. No.	Properties	Results	
		FA 1	FA 2
PHYSICAL			
1	Specific gravity	2.14	2.24
2	Fineness by Blaine (m^2/kg)	336	324
3	Soundness by Auto Clave Exp. (%)	0.03	0.04
4	Retention on 45µ IS Sieve by Wet Sieving (%)	22.3	29.0
5	Lime Reactivity (N/mm^2)	4.7	4.6
6	Compressive strength at 28 days as % of the strength of mortar cubes	86.2%	85.8%
CHEMICAL			
1	Loss on Ignition (% by mass)	0.14	0.12
2	Magnesium Oxide (% by mass)	0.89	1.15
3	Total Sulphur (SO_3) (% by mass)	0.19	0.13
5	Chloride (% by mass)	0.002	0.002
6	Alkali (% by mass)		
	Sodium Oxide	0.03	0.25
	Potassium Oxide	0.74	1.66
	Eq. as Na_2O	0.52	1.34
7	Silica (% by mass)	59.95	62.27
8	Iron Oxide (% by mass)	7.69	7.70
9	Alumina (% by mass)	26.23	23.18
10	Calcium Oxide (% by mass)	1.97	1.86

Table - 3 Test results of limestone powder sample

S. No.	Properties	Results Obtained	
		LS1	LS2
Physical Analysis			
1	BET fineness, m^2/kg	785	768
2	Specific Gravity	2.65	2.64
3	% Passing on 75 microns	99.5	99.8
4	% Passing on 150 microns	100	100
Chemical Analysis			
5	Loss on Ignition (% by mass)	40.32	39.19
6	Magnesium Oxide (% by mass)	1.11	2.19
7	Sulphuric Anhydride (% by mass)	0.10	0.13
8	Free silica	3.74	2.77
9	Chloride (% by mass)	0.007	0.005
10	Alkali (% by mass)		
	Sodium Oxide	0.10	0.19
	Potassium Oxide	0.19	0.22
	Eq. as Na_2O	0.23	0.33
11	Silica (% by mass)	3.74	4.39
12	Iron Oxide (% by mass)	0.73	0.88
13	Alumina (% by mass)	1.66	2.30
14	Calcium Oxide (% by mass)	51.69	50.17

Table - 4 Classification of limestone by Panda et al [30]

Category	**%CaO**	**Conventional Term Used**
I	48 – 52	High Grade
II	44 – 48	Cement Grade
III	40 – 44	Marginal Grade
IV	36 – 40	Low Grade

Table - 5 Limestone classification by Ramaiah et al [31]

Type	**% of Dolomite**	**Approximate MgO Equivalent**
High calcium limestone	Up to 10	0 – 2.17
Dolomitic limestone	10 – 50	2.17 – 10.86
Calcic dolomite	50 – 90	10.86 – 19.56
Dolomite	90 – 100	19.56 – 21.73

Physical characteristics of coarse aggregates are given in Table 6. The fine aggregate used was river sand conforming to Zone-II with water absorption, specific gravity, and fineness modulus as 0.8%, 2.66, and 3.10, respectively. In fine aggregate sample the material finer than 75-micron was 11.3 %. The coarse and fine aggregate properties meet the specifications of IS 383:2016 [33].

Table 6 - Test results of coarse aggregate

Sl. No.	Properties	A10	A20	A40	Limits according to IS 383:2016
1	Specific gravity	2.7	2.68	2.66	2.1 to 3.2
2	Water absorption (%)	0.41	0.43	0.59	Less than 5
3	Abrasion Value %	28	16	17	Less than 30
4	Crushing value %	22	19	15	Less than 30
5	Impact value %	19	13	13	Less than 30
6	Combined Flakiness and Elongation Index %	31	29.9	36.7	Less than 40
7	Soundness (Na_2SO_4) %	0.46	0.16	0.05	Less than 10
8	Total deleterious materials % (except coal & lignite)	0.1	0.1	0.1	Less than 2

2.1 Concrete mix composition

Three sizes of coarse aggregates, i.e., 40mm, 20mm and 10 mm and one fine aggregate sample was used in the study. Different proportions of coarse and fine aggregates were mixed and the compacted bulk densities were evaluated as per IS: 2386 (Part III) [34]. The compacted bulk densities of various combinations of fine aggregates (Sand) to coarse aggregates (A40/A20/A10) were determined. It was found that the compacted bulk density of aggregate ratio 20:22:28:30 was highest. With the obtained maximum aggregate proportion (20:22:28:30), different RCC mixes were prepared using two sources of fly ash and two sources of limestone powder. Corrections were made in adding water to account for aggregate water absorption. Similar to conventional concrete, aggregates for RCC must meet the specified standards for quality and gradation. Material Specification 524 [43], aggregates for RCC, mentions that quality of aggregate shall conform to ASTM C33 and grading shall be between a specific range. The gradation can be different than that normally used for conventional concrete. For example, the amount of material passing the No. 200 sieve is particularly greater for RCC than for conventional concrete and details for this are not laid down in IS: 383-2016 [33]. The larger percentage of fines is needed to fill voids in cement paste that would otherwise be filled with cementitious materials in case of conventional concrete [44-45]. Addition of fines are usually made up of naturally occurring non-plastic silt and fine sand or manufactured fines. Plastic fines should be avoided, as they cause increased water demand and lower strength. The overall combined grading curve for the aggregate blend is given in Figure 1A and Figure 1B. It shows that the combined grading lies between the specified limits according to ASTM C33 [35]

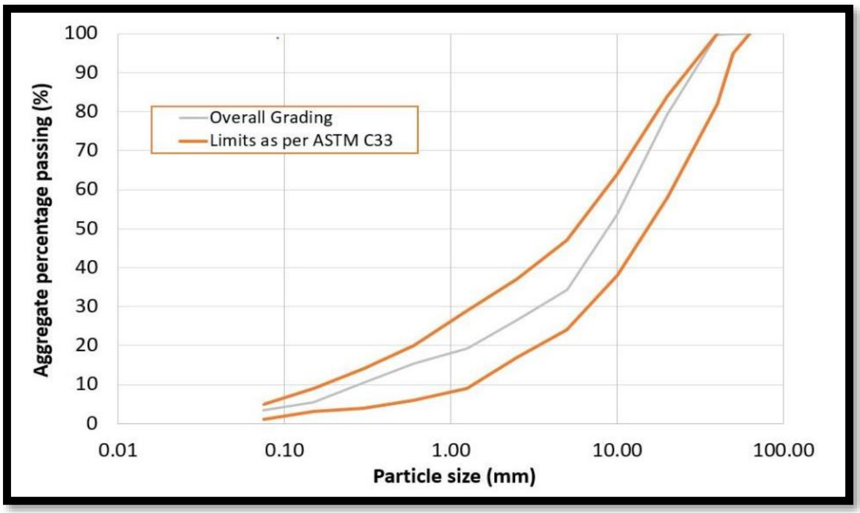
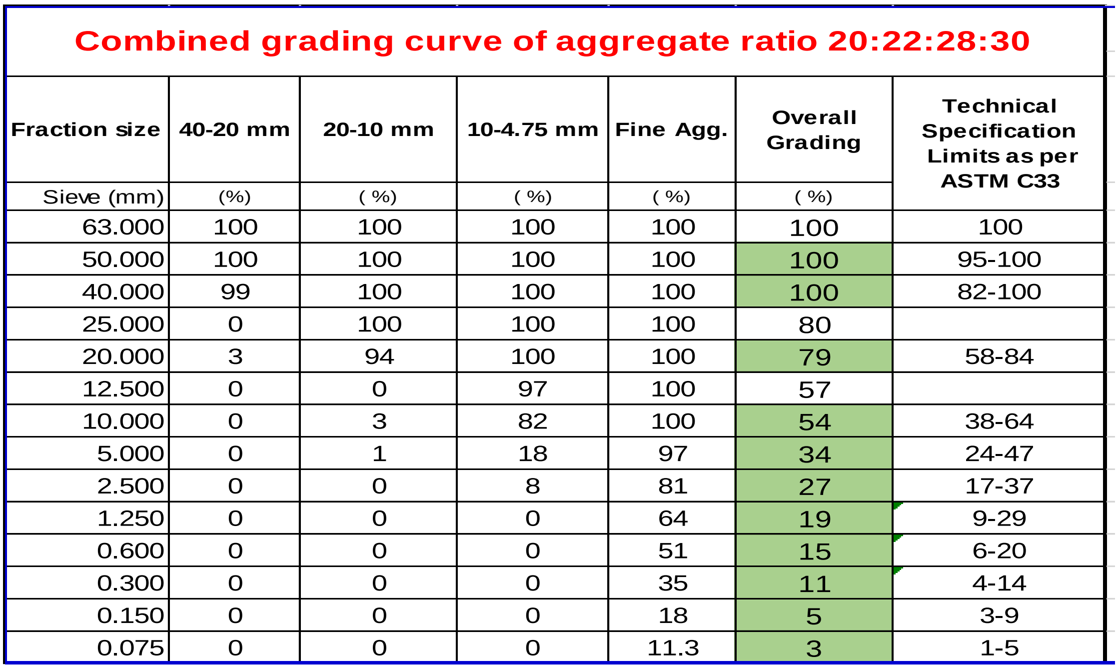


Fig. 1A – Combined grading curve of aggregate ratio 20:22:28:30



Combined grading curve of aggregate ratio 20:22:28:30

Fraction size	40-20 mm	20-10 mm	10-4.75 mm	Fine Agg.	Overall Grading	Technical Specification Limits as per ASTM C33
Sieve (mm)	(%)	(%)	(%)	(%)	(%)	
63.000	100	100	100	100	100	100
50.000	100	100	100	100	100	95-100
40.000	99	100	100	100	100	82-100
25.000	0	100	100	100	80	
20.000	3	94	100	100	79	58-84
12.500	0	0	97	100	57	
10.000	0	3	82	100	54	38-64
5.000	0	1	18	97	34	24-47
2.500	0	0	8	81	27	17-37
1.250	0	0	0	64	19	9-29
0.600	0	0	0	51	15	6-20
0.300	0	0	0	35	11	4-14
0.150	0	0	0	18	5	3-9
0.075	0	0	0	11.3	3	1-5

Fig. 1B – Grading of Aggregate Ratio 20:22:28:30

All the fractions of coarse aggregate along with fine aggregate were mixed in different ratios to achieve maximum bulk density of all in aggregate. The compacted bulk density was determined by following the procedure mentioned in IS: 2386 (Part III). The compacted bulk density of various combinations of fine aggregates and coarse aggregates (A40/A20/A10) are presented in Table-7. The RCC mix proportions are given in Table 8.

Table 7 - Bulk Density of All in Aggregate

S. No.	Trial ID	A40 (%)	A20 (%)	A10 (%)	Sand (%)	Total Wt. (Kg)	Wt. of Cylinder (Kg)	Wt. of Aggregate (Kg)	Vol. of Cylinder (Ltrs.)	Compacted Bulk Density (Kg/cum)
1	T1	21	21	28	30	76.90	16.31	60.09	29.17	2.007
2	T2	19	22	30	29	74.79	16.31	58.08	29.17	2.005
3	T3	25	19	25	31	75.26	16.31	58.45	29.17	2.001
4	T4	20	20	29	31	70.44	16.31	54.13	29.17	1.856
5	T5	22	23	24	31	72.84	16.31	56.58	29.17	1.940
6	T6	24	24	21	31	74.10	16.31	57.84	29.17	1.983
7	T7	21	21	28	30	73.63	16.31	57.37	29.17	1.967
8	T8	20	22	28	30	74.67	16.31	58.48	29.17	2.019

Table-8: Details of Roller Compacted Concrete Trial Mixes

Mix ID	Fly ash	Limestone	Total Cementitious content (Kg/m^3)	Cement (Kg/m^3)	Fly Ash (Kg/m^3)	Limestone (Kg/m^3)	Cement / Fly ash	Cement / Limestone	Cement / (Fly ash + Limestone)
1	FA1	-	210	70	140	-	0.50	-	0.50
2	-	LS1	210	110	-	100	-	1.10	1.10
3	-	LS1	210	90	-	120	-	0.75	0.75
4	-	LS1	210	70	-	140	-	0.50	0.50
5	-	LS2	210	110	-	100	-	1.10	1.10
6	-	LS2	210	90	-	120	-	0.75	0.75
7	-	LS2	210	70	-	140	-	0.50	0.50
8	-	LS2	210	60	-	150	-	0.40	0.40
9	-	LS2	210	120	-	90	-	1.33	1.33
10	FA1	LS2	210	80	70	60	1.14	1.33	0.62
11	FA1	LS2	210	100	35	75	2.86	1.33	0.91
12	FA2	LS2	210	110	50	50	2.20	2.20	1.10
13	FA2	LS2	210	60	70	80	0.86	0.75	0.40
14	FA1	LS1	210	80	70	60	1.14	1.33	0.62
15	FA1	LS1	210	100	35	75	2.86	1.33	0.91
16	FA2	LS1	210	110	50	50	2.20	2.20	1.10
17	FA2	LS1	210	60	70	80	0.86	0.75	0.40

Mix ID	Water (Kg/m^3)	Sand (Kg/m^3)	40mm (Kg/m^3)	20mm (Kg/m^3)	10mm (Kg/m^3)	W/C	Admixture (% by wt. of cementitious)
1	114	636	424	470	603	0.54	0.35%
2	120	686	450	454	566	0.57	0.35%
3	120	685	450	453	565	0.57	0.35%
4	120	684	449	453	565	0.57	0.35%
5	120	686	450	454	566	0.57	0.35%
6	120	685	450	453	565	0.57	0.35%
7	120	684	449	452	564	0.57	0.35%
8	120	684	449	452	564	0.57	0.35%
9	120	687	451	454	566	0.57	0.35%
10	117	661	448	472	563	0.56	0.35%
11	117	664	450	475	566	0.56	0.35%
12	117	664	450	475	565	0.56	0.35%
13	117	660	447	472	562	0.56	0.35%
14	117	661	448	473	563	0.56	0.35%
15	117	664	450	475	566	0.56	0.35%
16	117	664	450	475	565	0.56	0.35%
17	117	660	447	472	562	0.56	0.35%

2.2 Testing Methods and results

2.2.1 Consistency and density using Vee Bee method

Consistency of all the RCC mixes in fresh state was evaluated with Modified Vee Bee Consistometer as per procedure laid down in IS: 1199 (Part 2)-2018 [36]. This test gives the Vee Bee time of the concrete mix along with density of fresh concrete. For evaluation of consistency of different RCC mixes, concrete was placed in cylindrical mould in three different layers and was covered with a transparent acrylic disc. Cylindrical mould containing freshly filled concrete was vibrated to achieve proper compaction which will get the acrylic disc in complete contact with concrete surface. This test is a suitable way to evaluate the fresh properties in terms of consistency for concrete mixes having almost zero-slump. Under the action of vibration, cement paste in concrete rises to the surface. Consistency of the concrete mix is evaluated in terms of time required for concrete get consolidated by the external vibration.

2.2.2 Initial and final setting time of concrete mixes

All the concrete mixes were evaluated for the initial and final setting time of concrete. Initial setting time of concrete is time elapsed between initial contact of cement with water, till mortar (sieved from fresh concrete) acquires penetration resistance of 3.50 MPa. Final setting time of concrete is time elapsed after initial contact between cement and water, till mortar (sieved from fresh concrete) acquires penetration resistance of 27.60 MPa. The setting times for RCC mixes were evaluated as per IS 1199 (Part 7):2018 [32].

2.2.3 Compressive strength

Compressive strength of concrete mixes was evaluated on concrete cubes of size 150 mm × 150 mm × 150 mm. For preparation of cubes, molds were filled with concrete in three layers (each having approximate thickness of 50 mm) and after each layer concrete was compacted on Table vibrator for 60±2 seconds. Freshly filled concrete cubes molds (as shown in Figure 5(a)) were kept under laboratory conditions having temperature of 27±2°C and relative humidity ≥ 65% for 72 hours, till they gain sufficient strength. After 72 hours, concrete cube specimens were demolded and cured under water till the age of testing for compressive strength. Compressive strength was evaluated on cube specimen as per IS 516 (Pt-1/Sec-1): 2021 [38] at different ages of 7, 28, 56, 90 and 180 days.

3.0 Results and discussions

3.1 Vee Bee time and density

The Vee Bee time, Vee Bee density, total air free density for all the concrete mixes are presented in Figure 2 and 3**.** Total air free density for all mixes were almost similar and varied between 2450 to 2500 Kg/m^3. Similarly, degree of compaction (in terms of %) for all the concrete mixes were similar and varied in between 96.5 to 98.5%.

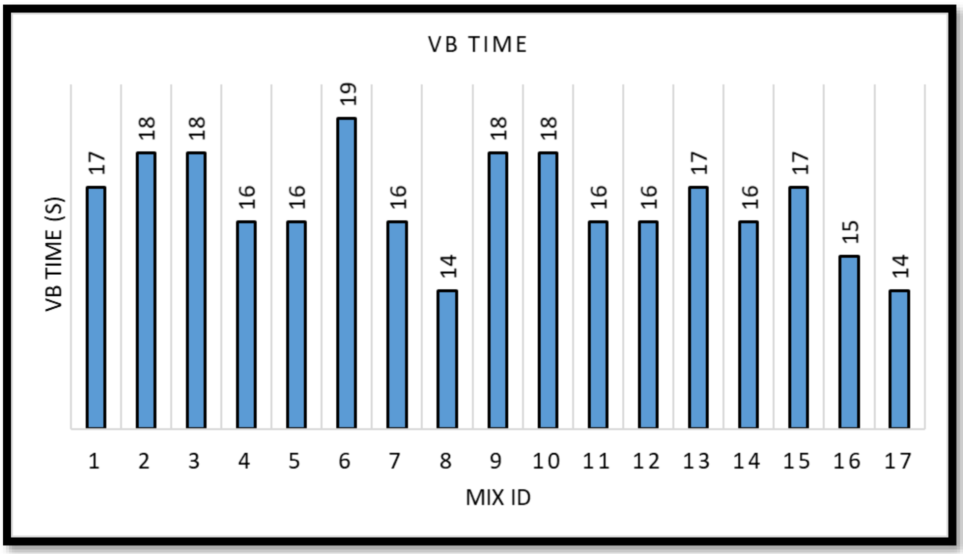


Fig. 2 – Vee Bee time for different concrete mixes

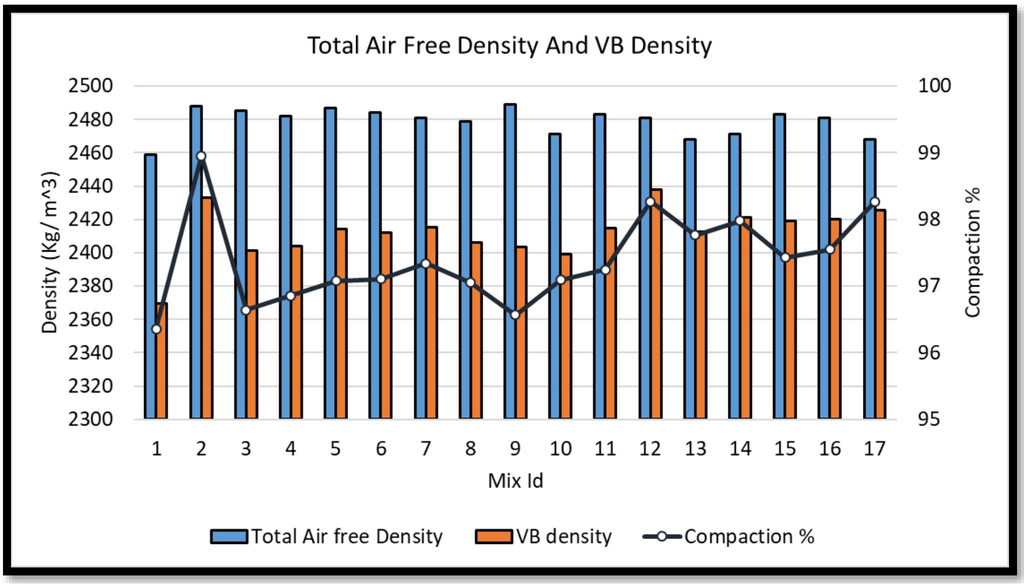


Fig. 3 – Density and degree of compaction for concrete mixes

3.2 Setting time of concrete mixes

The values of initial and final setting times are presented in Figure 4. Initial setting time for mix 1, is more than 20 hours 15 Minutes and final setting time is as high as 41 hours with fly ash and OPC which is also reported by Ojha et al [37]. A primary reason for this significant increase in setting time of RCC mix having fly ash can be attributed to the lubrication effect of fly ash due to its particle shape, low free lime content and high silica content along with delayed hydration of fly ash due to its pozzolanic behaviour.

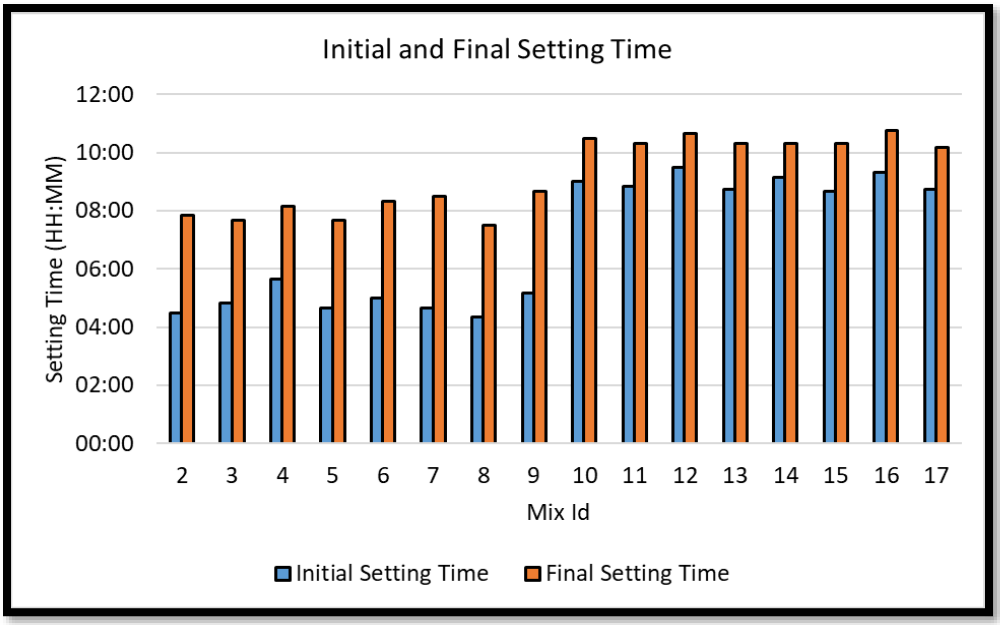


Fig. 4 – Initial and Final Setting time for different concrete mixes

For mixes 2 to 9, having OPC and limestone in varying proportions, initial setting time varies from 4 hours 30 minutes to 5 hours 40 minutes and final setting time varies from 7 hours 30 minutes to 8 hours 40 minutes. Both initial and final setting time of RCC mixes having OPC and limestone in varying proportion are significantly lower in comparison to mixes having fly ash and OPC. However, the variation in proportion of limestone in itself, does not have significant impact on setting time values, when mixes only have OPC and limestone as cementitious binders.

For mixes 10 to 17, having OPC, fly ash and limestone in varying proportions, initial setting time varies from 8 hours 45 minutes to 9 hours 30 minutes and final setting time varies from 10 hours 20 minutes to 10 hours 45 minutes. Both initial and final setting time of RCC mixes having OPC, fly ash and limestone in varying proportion are higher than the setting time observed in case of mixes having only OPC and limestone as cementitious binders. Increase in initial setting time is about 2 times, whereas increase in final setting time is about 1.5 times, when setting time of mix with limestone, fly ash and OPC (mix 10-17) is compared with mix having OPC and limestone (mix 2-9). Synergistic effect of fly ash and limestone in improving the setting time of mixes 10 to 17, indicates that maximum improvement achieved is 50% in initial setting time and 25% in final setting time as compared to setting time obtained in mixes with OPC and fly ash i.e. mix 1.

3.3 Compressive strength of concrete mixes

For analysis and comparison compressive strength of concrete mixes at different ages, all the mixes were categorized in three categories i.e. mixes with OPC content of 28 to 33%, mixes with OPC content of 38 to 48% and mixes with OPC content of 52 to 57% of total cementitious binder having varying proportions of fly ash and limestone. The compressive strength of aforementioned sets of concrete mixes have been shown in Figure 6, 7 and 8. In the figures 6, 7 and 8, proportion of individual components of total cementitious binder and compressive strengths at different ages are given on vertical Y axis while Mix ID for concrete mixes has been shown on horizontal axis.

Figure 5 shows compressive strength of concrete mixes with OPC content between 28% to 33% (by weight) of total cementitious content i.e. mix 1, 13, 17, 4, 7 and 8. Mix 1 comprises of PC and fly ash only. Mixes 4, 7 and 8 contain OPC and limestone. Mixes 13 and 17 are made up of ternary blends of OPC, fly ash and limestone.

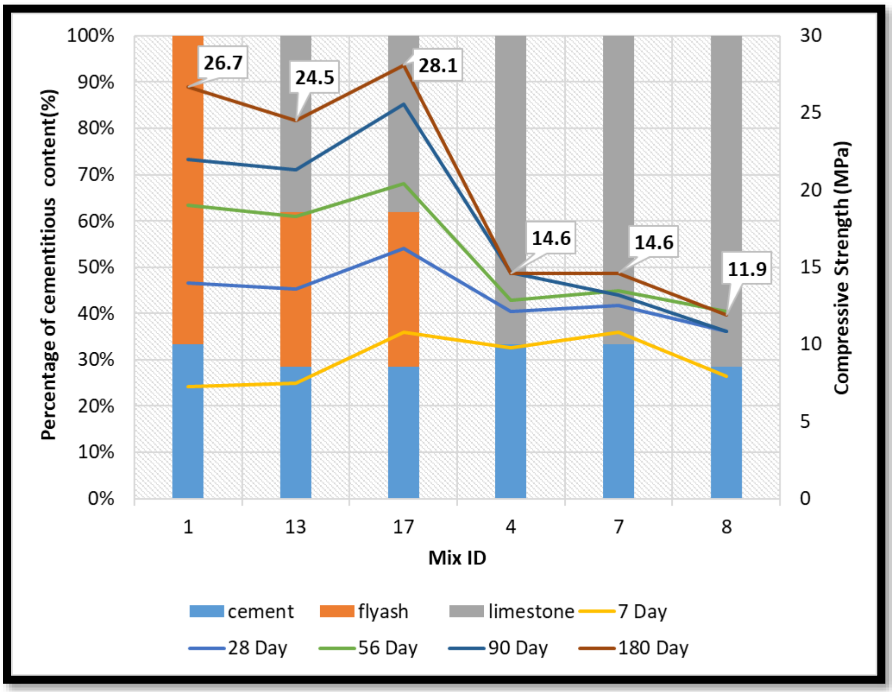


Fig 5 – Comparison of compressive strength of mix with OPC content between 28% to 33% (by weight) of total cementitious content

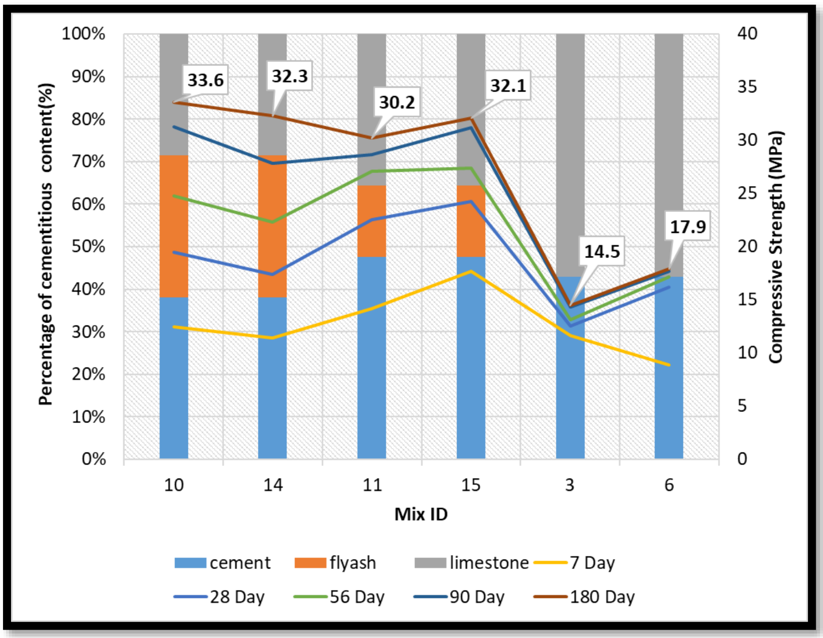


Fig 6 – Comparison of compressive strength of mix with OPC content between 38% to 48% (by weight) of total cementitious content

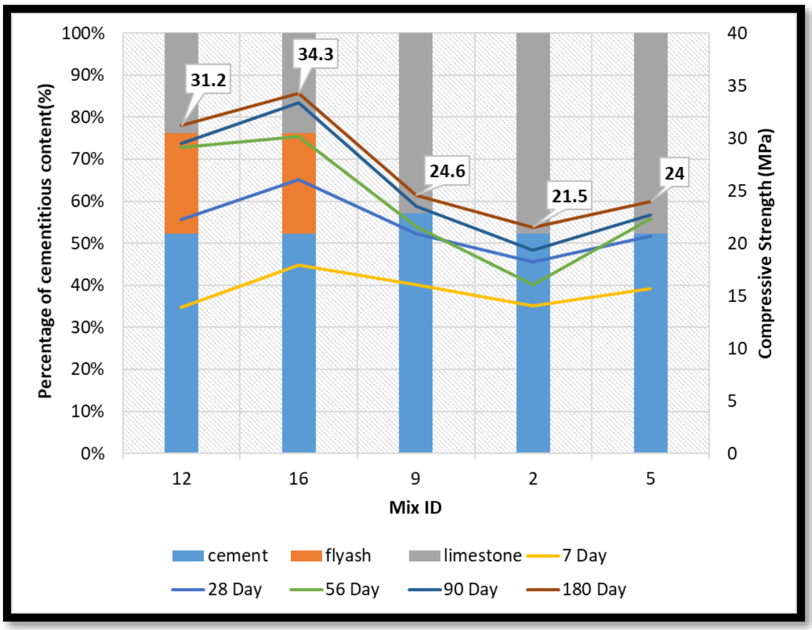


Fig 7 – Comparison of compressive strength of mix with OPC content between 52% to 57% (by weight) of total cementitious content

Figure 6 shows compressive strength of concrete mixes with OPC content between 38% to 48% (by weight) of total cementitious content i.e. mix 10, 14, 11, 15, 3 and 6. Mixes 3 and 6 contain OPC and limestone only. Mixes 10, 14, 11 and 15 are made up of ternary blends of OPC, fly ash and limestone. And Figure 7 shows compressive strength of concrete mixes with OPC content between 52% to 57% (by weight) of total cementitious content i.e. mix 12, 16, 9, 2 and 5. Mixes 9, 2 and 5 contain OPC and limestone only. Mixes 12 and 16 are made up of ternary blends of OPC, fly ash and limestone.

Early age strength at 7 days is observed to be higher for mixes containing high proportion of limestone and OPC (mix 2 to mix 9) in comparison to mixes having only fly ash as replacement of OPC (mix 1) as presence of limestone will effectively increase water to OPC ratio, and provide additional surface for precipitation of hydration products, thereby promoting the early age hydration of the OPC resulting into higher early age strength. However, with increase in age, hydration reactions of fly ash come into picture, as alumino silicates present in fly ash react with portlandite being produced during hydration of OPC, which will improve the strength at later ages. For mixes, only having OPC and high proportion of limestone, once the majority of hydration of OPC occurs during early days, there is no significant improvement in strength at later ages, as limestone will not contribute to strength gain in this case and will only act as filler. Therefore, there is no significant strength gain for such mixes after 28 days.

For mixes having fly ash and limestone both along with OPC as cementitious binder (i.e. mix 10 to mix 17), synergic effect of presence of limestone, fly ash and OPC comes into picture, as limestone powder seems to promote the early age hydration [39, 40] more than fly ash as the compressive strength tends to increase as limestone replaces fly ash. At later ages, apart from filler effect of limestone, chemical effect of limestone also comes into picture. The calcium carbonate of the limestone powder will interact with the aluminate hydrates formed by hydration of OPC and fly ash [41, 42]. Calcium monosulphoaluminate hydrate is unstable in the presence of calcium carbonate, and instead calcium mono- and hemicarboaluminate hydrate will form. This leads to the stabilization of ettringite and will result in an increase in the total volume of the hydration products [35, 36], which potentially might result in a decrease in porosity and thus an increase in strength, which gets reflected in the compressive strength results of mixes having fly ash and limestone both along with OPC as cementitious binder at later ages.

Therefore, for mixes in all the three categories i.e. mixes with OPC content of 28 to 33% (i.e. mix 1, 13, 17, 4, 7, 8), mixes with OPC content of 38 to 48% (i.e. mix 10, 14, 11, 15, 3, 6) and mixes with OPC content of 52 to 57% (i.e. mix 12, 16, 9, 2, 5) of total cementitious binder having varying proportions of fly ash and limestone, mixes having fly ash and limestone both along with OPC as cementitious binder (i.e. mix 17, 10 and 16 within their individual categories of OPC content) gave best results in terms of compressive strength.

4. Conclusions

The study presents an experimental investigation on the effect of the variations in the fly ash and limestone content on the fresh and hardened properties of RCC. Properties studied includes consistency, Vee Bee density, setting time and compressive strength. Based on the findings from the experimental study following points can be concluded as given below:

- The varying proportions of fly ash and limestone in total cementitious binder does not seem to have any significant impact on the air free density and degree of compaction as total air free density and degree of compaction for all mixes were almost similar and comparable.
- Both initial and final setting time of RCC mixes having OPC and limestone in varying proportions (i.e. mix 2 to mix 9) are significantly lower in comparison to mix having fly ash and OPC (mix 1) due to nucleation effect of finer limestone promoting early age hydration of the OPC resulting into higher early age strength.
- However, for mixes having combination of OPC, fly ash and limestone as cementitious binder (i.e. mix 10 to mix 17), setting time is somewhere in between setting times of concrete mixes made with binary cementitious systems (i.e. OPC and limestone & OPC and fly ash) due to the synergistic effect of both fly ash and limestone.
- Early age strength for mixes containing limestone and OPC (i.e. mix no. 2 to mix no. 9) in comparison to mixes having only fly ash as replacement of OPC (mix 1) was observed to be higher due to nucleation effect of limestone. However, after hydration of OPC at early ages, no significant improvement in strength will occur for such mixes. For mixes having fly ash and OPC (mix 1), compressive strength will be higher due to hydration of fly ash at later ages.
- Optimum performance in terms of compressive strength at all the ages was observed for mixes with ternary cementitious system (i.e. mix no.17, 10 and 16 in their individual categories of OPC content) having both fly ash and limestone with OPC as cementitious binder, due to role of limestone in promoting early age hydration of OPC which give required early age strength to the concrete. At later ages, compressive strength of mix will develop progressively due hydration of fly ash at later ages. Along with that, aluminates present in fly ash will also get limestone to interact chemically as calcium carbonate present in limestone will react with the aluminate hydrates formed by hydration of OPC and fly ash and develop additional hydration products (hemi and mono carbo aluminates) resulting into improved compressive strength.

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