Research Article

STRENGTH PROPERTIES OF HIGH WORKABLE AND HIGH VOLUME FLY ASH ROLLER COMPACTED CONCRETE

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ABSTRACT

This paper describes research on strength properties of high workable and very high volume fly ash Roller compacted concrete (RCC). The mixes were developed through incorporating 50 - 260kg/m^3 cement and very high volumes of fly ash ranging from 40 to 85% by mass of total cementitious material. The results shown that the RCCs were more workable and easy compactable. The compaction time for the mixes was between 15-20sec only. The concretes were investigated for compressive strength, split tensile strength, modulus of elasticity, rebound hammer number and ultrasonic pulse velocity. As other properties of concrete are frequently expressed in terms of compressive strength, the properties of these very high volume RCCs were compared with compressive strength and compared with existing empirical equations for normal concrete.

KEY WORDS: Dam construction, Fly ash, Pavement, Roller compacted concrete, Strength

1. INTRODUCTION

Global warming has alarmed engineers to develop environmentally friendly methods and techniques to cater needs of modern society. Consequently, intense research has been conducted in civil engineering field for construction industry. Concrete technologists focused their research into optimise use of cement and natural aggregate for environmentally friendly and sustainable construction. Several investigations were conducted with mineral admixtures such as fly ash, silica fume, metakaolin and other materials as cement replacement[1-6]. Recycled aggregate, crushed sand, recycled glass, chinaclay sand, foundry sand and other waste materials were incorporated either partially or fully for natural aggregates in concrete and investigated properties of these concretes [7-9]. The concretes thus developed can result dual benefits such as: (i) reduced use of cement and natural mineral aggregate and (ii) increased use of waste materials, which are otherwise sent to landfills.

Fly ash is one of the industrial by-products produced abundantly throughout the world. Annual fly ash production in India is 112 million tons followed by China with 100 million tones and USA with 75 million tonnes. However, utilization is 38%, 45% and 65% in India, China and USA respectively [10]. Unused quantities of fly ash create landfill and environmental problems. These problems can be avoided with increased use of fly ash. Literature shows incorporation of high volumes of fly ash that is, 50-80% is possible in roller compacted concrete (RCC) [11-13]. RCC is a special form of concrete for construction of dams and pavements [14]. RCC is a stiff mixture of cementitious material, aggregates and water. It differs from normal concrete in consistency. Consistency of RCC should be such that, the mixture should support roller while compaction [14]. It is found to be the least labour intensive and almost free from transverse cracking, a major problem with conventional wet lean concrete [14]. With minimal equipment RCC can rapidly be placed, which results speedy completion of the project [14]. Therefore, increased use of RCC in construction of dams, pavements and works can yield benefits of use of high volume fly ash coupled with construction technique.

There were few studies on high volume fly ash RCCs. Cao et al (2000) [11] replaced cement with fly ash up to 72%. The total cementitious material maintained constant at 300kg/m^3. The water to cementitious material ratio was between 0.33 to 0.35. Reported 90 day compressive strength was between 39 to 66MPa.

Tangtermsirikul et al (2004) [12] developed fly ash RCC compressive strength model. The fly ash percentage was between 20 to 80%. The water to cementitious material ratio ranged from 0.30 to 0.40. The cement quantity was between 50 to 376kg/m^3. They reported 22 - 70MPa compressive strength at 90 day curing.

Atis (2005) [13] investigated strength properties of high volume fly ash RCC. The mixes was developed with 400kg/m^3 of total cementitious material and incorporated 50 and 70% of fly ash maximum cement content was 400kg/m^3 and minimum cement content was 120kg/m^3. Water to cementitious material ratio was between 0.29 to 0.4. Reported 28 day compressive strength was 22 to 67 MPa.

As stated earlier, suitable consistency is necessary for RCC mixture to support roller during compaction and achieve compaction or consolidation. Sufficient workability is also necessary for acceptable appearance when RCC is to be compacted against forms [14]. Workability is most affected by the paste portion of the mixture including cement, pozzolan, aggregate fines, water and air [14]. In general the vebe time of RCC mixes varies between 10 to 120s [14-15]. Low compaction time (vebe time < 20s) indicates high workable RCC mixes. For reduced compaction energy, it is necessary to have less vebe time of compaction and thus to make RCC more sustainable. Suitable amount of paste is also important to fill or nearly fill aggregate voids and produce a compactable dense concrete mixture. Workability and paste volume should also be necessary to produce bond and watertightness at the horizontal lift joints, when RCC mixture is placed and compacted quickly on a reasonably fresh joint. At very low cement contents it may be difficult to generate sufficient paste in the mix with available fines from cement and aggregate alone. Investigations towards workable and very low cement RCCs is scanty.

Thus, in the present investigation very low cement content was used and high volumes of fly ash was added for workable (vebe time < 20 Sec) RCCs and high paste mixes were developed even at very low cement contents. The performance of these concretes was assessed through strength and transport properties. In this paper, only strength characteristics such as compressive strength, split tensile strength and modulus of elasticity results are presented. The transport properties like permeability, water absorption, permeable voids, sorption and chloride diffusion were published elsewhere [16].

The present laboratory investigations were conducted in the materials and structures laboratory of Ocean Engineering Department in Indian Institute of Technology Madras in India.

2. EXPERIMENTAL INVESTIGATIONS

2.1. Materials

Ordinary Portland cement of C53 grade conforming the requirements of IS: 12269 [17] and ASTM C 642-82 type I [18] and Class F fly ash conforming to the ASTM C 618 [19] was used. Physical characteristics and chemical compositions of the materials are given in Table 1. Well graded river sand finer than 2.36 mm fine aggregate and normal course aggregate, that is, crushed blue granite of 20 mm maximum size was chosen as coarse aggregate. Relative densities of fine and coarse aggregates were 2.61 and 2.63 respectively at SSD. Water absorptions were 1.0% and 0.82% for fine and coarse aggregates respectively. Combined well graded aggregate grading was obtained through mixing of coarse aggregate passing through sieve sizes of 20 mm and 12.5 mm and fine aggregate finer than 2.36 mm. Potable water was used for mixing and curing. All the constituent materials used in this investigation were procured from local sources.

Table 1 Chemical composition and physical characteristics of cement and fly ash

	CEMENT	FLY ASH
Chemical Composition (%)		
Silica (SiO_2)	21.8	58.3
Alumina (Al_2O_3)	6.6	31.7
Ferric oxide (Fe_2O_3)	4.1	5.9
Calcium oxide (CaO)	60.1	2.0
Magnesium oxide (MgO)	2.1	0.1
Sodium oxide (Na_2O)	0.4	0.8
Potassium oxide (K_2O)	0.4	0.8
Sulphuric anhydride (SO_3)	2.2	0.2
Loss on Ignition (LOI)	2.4	0.3
Physical Characteristics		
Fineness (Blaine), m^2/kg	307	350
Standard consistency, %	33	NA
Normal consistency, %	28	NA
Specific gravity	3.15	2.06
Initial setting time, min	205	NA
Final setting time, min	287	NA
Compressive strength, N/mm^2		
1 day	24	NA
3 days	37.5	NA
7 days	49.5	NA
28 days	65	NA

2.2. Mix proportions

As stated in S*ection 1.0* the mixes were proportioned to have low vebe compaction time and high paste content. Cement content was maintained between 50 to 260 kg/m^3 and fly ash percentage was ranged between 40 to 85%, high sand to aggregate ratio was chosen (0.47) to minimize voids in coarse aggregate. In common the sand to aggregate ratio varies from 0.34 to 0.42 [12, 15]. However, before arriving at final mix proportions and suitable water to cementitious material ratio, extensive laboratory investigations were conducted. In total six mixes were proportioned, two were created with very low cement and very high fly ash content (RCC1 and RCC2); two of low cement and high fly ash content (RCC3 and RCC4); and remaining two of moderate cement and moderate fly ash content (RCC5 and RCC6). Details of the concrete mixes are presented in Table 2.

Table 2 Mixture proportions

Mix	c, kg/m^3	fly ash, kg/m^3	f/(c+f) %	w, kg/m^3	w/(c+f)	CA, kg/m^3	FA, kg/m^3
RCC1	50	283	85	170	0.51	1024	750
RCC2	90	270	75	163	0.45	1024	750
RCC3	150	350	70	153	0.31	996	729
RCC4	190	285	60	170	0.36	1111	813
RCC5	250	167	40	160	0.38	1114	816
RCC6	260	260	50	180	0.35	1003	735

c – cement, f – fly ash, w – water, CA – coarse aggregate and FA – fine aggregate

2.3. Mixing, compaction, specimen preparation and curing

The concretes were mixed in a planetary mixer of 100 l capacity. The mixing time kept to about 3 to 4 min. Mixing of the materials was in a sequence: (i) portion of design water poured into mixture drum; (ii) coarse aggregate placed and spread it to the boundaries of the mixture drum; (iii) cement and fly ash gently placed over the aggregate; and (iv) sand was spread over the powder and started mixing. During mixing, the remaining design water was poured into the mix so that the concrete could mix thoroughly. Specimens were then prepared in accordance with ASTM C1176 [20]. They were compacted in three equal layers and each layer was compacted with top surcharge of 5 kPa. Compaction was continued until a paste ring was observed between the periphery of the surcharge and the cylinder or cube. The compaction time of each layer for all the concretes did not exceed 20 sec; the compaction time was nearly within 15 - 20Sec range. The moulds were then covered with wet gunny bags until demoulding. The specimens were demoulded after 24 hours and immersed in normal water for curing until the test age.

3. TEST PROGRAM

The main objective of the present investigation was to develop high workable and high paste RCCs with no chemical admixtures in the mixes and study the performance of these concretes. Performance of the concretes was assessed through: fresh properties, compressive strength, split tensile strength and modulus of elasticity.

3.1. Properties of fresh concrete

Visual inspections were conducted to assess appearance, segregation, uniformity in the aggregates during mixing and compaction. Furthermore, broken compression and split tensile test specimens were also inspected for evaluating fresh concrete parameters such as segregation; uniformity in the aggregates and layer joint behaviour of the concretes. Consistency and density of RCCs was measured as per ASTM C1170 [21]. Vebe table was used to measure consistency of RCCs. The time for a given mass of concrete to be consolidated by vibrating in cylindrically shaped mould with surcharge of 22.7kg (5kPa pressure) was considered as vebe compaction time of RCCs or consistency of RCCs. Densities of the compacted specimens was then measured by mass and volume parameters of the consolidated specimens.

3.2. Compressive strength studies

The compressive loading tests on concretes were conducted on a compression testing machine of capacity 2000 kN. For the compressive strength test, a loading rate of 2.5 kN/s was applied as per IS: 516–1959 [22]. The test was conducted on 100mm cube specimens. The test was performed at 7, 28 and 90 days. The specimens were completely water cured until test age. The specimens were then tested immediately after taking the cubes from curing tank in wet condition.

3.3. Split Tensile Strength

Split tensile strength test was conducted in accordance with ASTM C496 [23]. Cylinders of 100 x 200 mm size were used for this test, the test specimens were placed between two platens with two pieces of 3 mm thick and approximately 25 mm wide plywood strips on the top and bottom of the specimens. Split tensile strength test was conducted on specimens after 90 days of curing.

3.4. Modulus of Elasticity

Static modulus of elasticity test was conducted in accordance with ASTM C 469 [24]. Cylinders of 100 x 200 mm size were used for this test. This test was conducted on two replicate specimens after 90 days of curing.

3.5. Rebound hammer

Relative hardness of concrete can be estimated through rebound hammer test and it is possible to correlated compressive strength of concrete with this number. In present investigation rebound hammer test was conducted using Rebound Hammer (Schmidt hammer) as per the specifications given in ASTM C805 [25]. On each face of 100 mm cube about 5 readings were taken before compressive strength test after applying a preload of about 10% of design failure load. The readings were taken on smooth surface. Average value of all the readings was taken as index number of all RCCs.

3.6. Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) test was conducted using an ultrasonic tester from Marui, Japan (MIN-020-1-00, UST) transducers of 50 kHz frequency. UPV test was conducted as per the specifications given in ASTM C 597 [26]. Time taken for the pulse to travel from transmitter to receiver placed on opposite sides of the 100 mm concrete cubes was measured. Transducers were placed on cleaned and greased surface to avoid air gapes between the specimen surface and transducers. Pulse velocity readings were taken at the age of 90 days for all RCCs.

4. RESULTS AND DISCUSSION

4.1 Fresh properties

Higher volumes of fly ash in the RCCs resulted in an excellent performance as observed during the compaction and testing. The vebe compaction time for all the RCCs was less than 20sec, indicating the mixes are more workable. During compaction sufficient paste was observed in all the RCCs including for very low cement mixes (RCC1 and RCC2). Sufficient paste in all the mixtures around the course aggregate particles avoided point to point contact between the coarse aggregate particles and aided in good compaction of RCCs. The densities of the concretes were ranged from 2275 to 2562 kg/m^3. Higher densities in RCC than conventional concretes can be attributed to lower water content and higher solids. While testing the specimens for compression and split tensile failure, no joint separation was observed. This observation thus indicates that there was good bond between the layers of RCC. Bond between the layers is an important parameter in RCC mixture [14]. Furthermore, smooth surface finish was observed in all the RCCs, even at very low cement content (RCC1 and RCC2). Smooth surface finish is an important parameter for pavement applications. Use of high volumes of fly ash in the RCCs resulted benefits like: low compaction time, good compaction, higher densities, good bond between the layers and good surface finish, even for very low cement content. From Table 2 it can be observed that irrespective of amount of cement content the water to cementitious material ratio decreased with increase in total cementitious material for full compacted RCCs. Therefore, high fly ash volumes in RCCs is also advantageous to increase total cementitious material and thus to decrease water to cementitious material ratio with no compromise at workability of RCC.

4.2 Compressive strength

The average compressive strength obtained from three replicate specimens is shown in Table 3. As shown, the result indicated that the compressive strength of the concretes was between 7 to 35 MPa for 7 day, 32 to 48 MPa for 28 day and 19 to 61 MPa for 90 day. The results are in line with previous RCC investigations (Table 4). Understanding strength to time relationship is of importance when a structure is to be put into use that is, subjected to full loading.

Table 3. Engineering properties the concretes investigated.

Concrete name	Density, kg/m^3	Compressive Strength (f_c), MPa			Rebound Hammer Number			UPV, km/sec	f_t, MPa	E_{50}, GPa
		7d	28d	90d	7d	28d	90d			
RCC1	2275	7	13	19	22	25	31	3.57	1.85	17
RCC2	2302	13	21	26	26	27	30	4.55	3.18	28
RCC3	2403	18	28	38	27	32	42	4.35	3.5	34
RCC4	2562	20	36	46	28	37	41	4.55	3.95	33
RCC5	2498	32	41	50	35	37	46	4.35	4.14	41
RCC6	2441	35	48	61	37	40	45	4.35	4.46	42

UPV- ultrasonic pulse velocity; ST-split tensile strength;
E_{50} - modulus of elasticity at 50% ultimate strength

Table 4 Fly ash RCC mixes from literature

Author	c, kg/m^3	f, kg/m^3	w, kg/m^3	w/(c+f)	Compressive strength, Mpa		
					7d	28d	90d
Tangtermsirikul, 2004 [12]	49	194	87	0.36	6.8	15.7	22.3
	258	65	116	0.36	43.6	52	64.4
	245	61	122	0.40	31.4	47.5	57
	53	51	113	1.09	2.1	4	7
	94	207	89	0.30	14.1	23.6	29
ACI, 1999 [14]	104	47	110	0.73	7.9	14.2	27
	47	19	107	1.62	4.1	8.1	11.9
	187	18	109	0.53	14	23.5	30.8

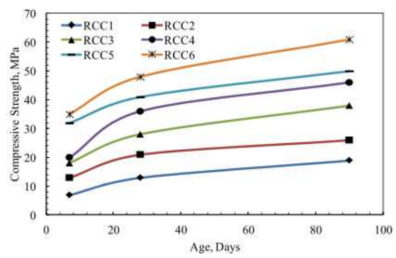

Figure1. Compressive strength gain as a function of time after casting

Fig. 1 shows the influence of varying curing ages on compressive strength of fly ash RCCs. Strengths increased with age for all RCCs, in the first seven days of curing an average increase in strength was

74, 68 and 33 percent for very high volume fly ash (RCC1 and RCC2), high volume fly ash (RCC3 and RCC4) and moderate fly ash (RCC5 and RCC6) concretes of its 28 day compressive strengths respectively. After 90 days of curing, the 28 day compressive strength had exceeded by an average of 35, 32 and 25 percent for very high volume fly ash (RCC1 and RCC2), high volume fly ash (RCC3 and RCC4) and moderate fly ash (RCC5 and RCC6) concretes of its 28 day compressive strengths respectively. This observation suggests that although overall strength was lower than high volume fly ash and moderate fly ash RCCs due to lower cement content, the strength rate was higher for very high volume fly ash RCCs with curing period.

Presence of very high fly ash quantities in the concrete mixes help cement for complete participation in pozzolanic reaction with fly ash and excess fly ash which could not participate in the pozzolanic reaction acts as filler [27]. Therefore, the predominant component which influences strength of the concretes with higher fly ash quantities is cement quantity. Evidently, irrespective of variation of total cementitious material in the concretes there was good agreement between cement content and strength of the concretes for all curing ages (Fig. 2).

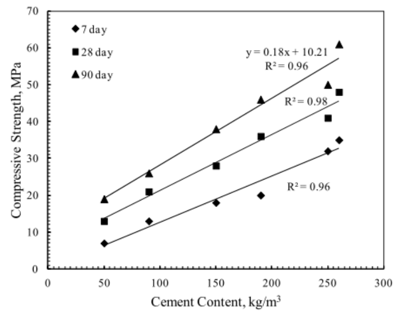

Figure 2 Influence of cement content on compressive strength for different curing ages

Fig. 3 presents strength to cement ratios for the concretes investigated. From the figure it can be understood that very high volume fly ash RCCs had high strength to cement ratio followed by high volume fly ash RCCs and moderate fly ash RCCs. This observation suggests that it is possible to obtain maximum benefit with cement at very high volume fly ash contents. Therefore, depending on the project type and strength requirement it may be advantageous to choose appropriate cement quantity and possible maximum fly ash quantity in RCCs for workable and economical concrete. As stated earlier, increased fines in the mixes decreased required water to total cementitious material ratio for workable RCCs and subsequently could have contributed higher strength apart from cement content in the concretes.

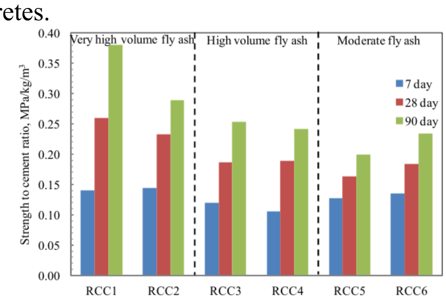

Figure 3 Strength to cement ratios for RCCs investigated at different test ages

4.3. Split tensile strength:

Tensile strength of concrete is of interest for some purposes, for example, the design of highway and airfield pavements, shear strength, and resistance to cracking. Therefore, understanding the tensile strength behaviour and relationship between compressive strength and tensile strength with different fly ash percentages in RCC is useful. The average split tensile strength obtained from two replicate cylinder specimens at 90 day curing age is shown in Table 3. As shown, the result indicated that the split tensile strength of the concretes was between 1.8 to 4.8Mpa for 90 days. The influence of cement content on splitting tensile strength is depicted in Fig. 4 for mixture proportions used in this investigation. It can be observed that similar to compressive strength, the splitting-tensile resistance improved with increasing cement content.

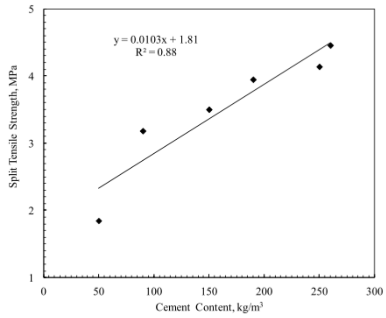

Figure 4 Influence of cement content on splitting tensile strength at 90 day curing age

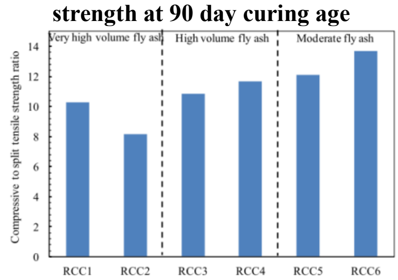

Figure 5 Compressive to split tensile strength ratios for RCCs investigated at 90 day curing Age

Ratios of compressive to splitting-tensile strengths for the concretes investigated is shown in Fig. 5 from the figure it is clear that the ratio varied from 8.2 to 13.7. Furthermore, from the figure it can also be noticed that the ratio was higher for moderate fly ash mixes, suggesting increase in cement content is more advantageous for compressive strength than split tensile strength. In other words presence of high volumes of fly ash improves splitting tensile resistance more than it does compressive strength.

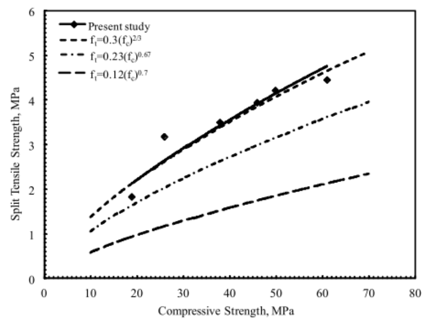

Figure 6 Relationship between compressive strength and split tensile strength

Fig. 6 shows relationship between compressive strength and split tensile strength, from the figure it can be observed that, as compressive strength increased split tensile strength also increased.

Irrespective of different constituent quantities in the RCCs, a good power relationship was observed between the variables with regression coefficient of 0.88. There exist various empirical relationships to relate the compressive strength of concrete to its tensile strength. Some of the prevalent published relationships are shown in Equations from (1) to (3). Equation (1) was suggested by Raphael, 1984 [28] for normal concrete. Equation (2) was suggested by FIP, 1991 [29] for light weight aggregate concrete. Equation (3) was used in the British Code of Practice BS 8007:1987 [30] where the compressive strength is determined on cubes in MPa, ft is the direct tensile strength.

In Fig. 6 the trend of present data with different standard relationships was compared. Although the compressive strength was obtained on cube specimens in the present study, a close association was observed with Equation (1). However, large data is needed to characterize the relationship.

$f_t = 0.3(f_c)^{2/3}$ (1)

where f_t is the splitting strength, and f_c is the compressive strength of cylinders, both in MPa.

$f_t=0.23(f_{cu})^{0.67}$ (2)

where f_t is splitting strength and f_{cu} is compressive strength measured on cubes both in MPa.

$f_t=0.12(f_c)^{0.7}$ (3)

where the compressive strength f_c is determined on cubes in MPa, f_t is the direct tensile strength.

4.4. Modulus of elasticity

The modulus of elasticity evaluated for the concretes is shown in Table 3. As shown, the result indicated that the modulus of elasticity of the concretes was between 17 to 46 GPa for 90 days of curing. From Table 3 it can also be observed that the behaviour of modulus of elasticity is similar as that of compressive and split tensile strengths.

Various empirical relationships exist to relate compressive strength of concrete to its modulus of elasticity. Two widespread equations were shown in Equation (4) and (5). Equation (4) is widely used relationship for normal strength concrete suggested by ACI Committee 318, 2005 [31]. Equation (5) was suggested by ACI363R [32] for high strength concretes up to 83MPa. A comparison of these relationships to the data obtained in this study was made. The data, which was the basis for this analysis, along with the modulus results for strengths are shown in Fig. 7. This figure also graphically presents the ACI 318 and ACI 363R Equations (4) and (5). From the figure it is clear that the relationship between compressive strength and modulus of elasticity is overestimated at higher strengths. Although the figure gives preliminary idea about the relationship, large data is needed to characterize the relationship. A predictor Equation (6) was developed for high volume fly ash RCCs. This relationship is shown in Fig. 7 the relationship exhibits R-squared value of 0.9.

$E = 4.73f_c^{0.5}$ (4)

where E is modulus of elasticity expressed in GPa and fc in MPa

$E = 3.32f_c0.5+6.9$ (5)

For concretes with strengths up to 83MPa, where E is modulus of elasticity in GPa and f_c in MPa.

$E = 2.31f_c^{0.72}$ (6)

where E is expressed in GPa and fc is cube compressive strength in MPa

4.5 Rebound Hammer Number

The rebound hammer number evaluated for the concretes is shown in Table 3. As shown, the result indicated that the rebound hammer number of the concretes was between 22 to 37, 25 to 40 and 30 to 45 for 7, 28 and 90 days respectively. From Table 3 it can also be observed that the trend is similar to compressive strength for the RCCs. Furthermore, it can be observed that for all the concretes the rebound number increased with age. As rebound number is indirect measure of strength of concrete, a relationship between compressive strength and rebound hammer number was observed (Fig. 8). A good positive linear relationship was observed between compressive strength and rebound hammer number. Fig.7 shows comparison between fly ash RCC and normal concrete strength to rebound hammer relationships. Relationship shown in Fig. 8 for normal concrete compressive strength with rebound hammer number is from Neville, 1995 [33]. From the figure it can be observed that up to 20 MPa compressive strength the rebound hammer number is higher for RCCs than normal concrete for corresponding strengths and beyond 20MPa the rebound hammer number is lower than normal concrete for RCCs. Furthermore, it can also be observed that at the age of 90days the rebound hammer number for all the concretes was higher than 30, showing that good layered and very good hard layered concretes as per ASTM C805 [25] assessment criteria.

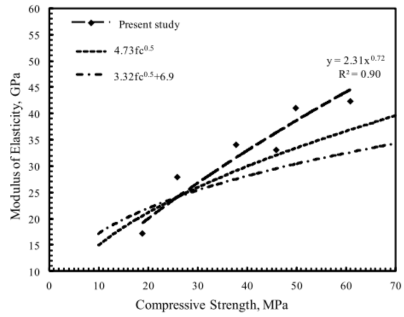

Figure 7 Relationship between modulus of elasticity and compressive strength

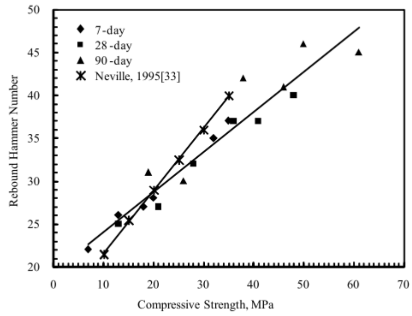

Figure 8 Relationship between rebound hammer number and compressive strength

4.6 Ultrasonic pulse velocity

The ultrasonic pulse velocity evaluated for the concretes is shown in Table 3. As shown, the result indicated that the ultrasonic pulse velocity of the concretes was between 3.57 to 4.55 km/sec for 90 days. Except RCC1, there was no big variation between the UPV values for other concretes were observed. Furthermore, unlike rebound hammer number, no relationship was observed between compressive strength and UPV (Fig. 9). From Fig. 9 it can be observed that as per ASTM C597 [26] assessment criteria all concretes falling under very good quality class except RCC1. Therefore this observation suggests that it is possible to produce very good quality RCC even with very low cement that is 90kg/m^3 and very high fly ash that is 80% by mass of total cementitious material.

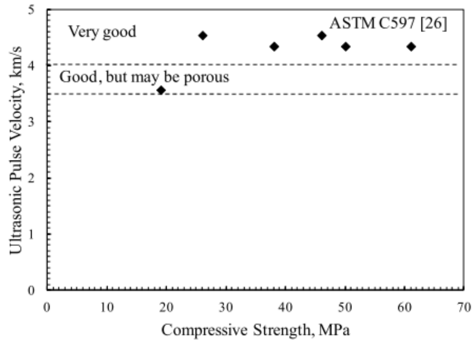

Figure 9 Relationship between compressive strength and ultrasonic pulse velocity

Apart from the engineering properties discussed in this paper, the transport properties of these concretes was also investigated and published elsewhere. The performance of the concretes in terms of transport properties was also good. The result shown that coefficient of permeability of these concretes was between 6.9-106 x 10^{-12} m/s. From the permeability values it was noticed that less permeable (7–10x10^{-12}m/s) fly ash RCCs can be produced with cement ranging from 150 to 190kg/m^3 and fly ash percentage ranging from 60% to 70%, with vebe compaction of 15–20s. The maximum water absorption observed was 2.11% for 85% fly ash RCC. Overall all the concretes were under good quality as per CEB-FIP (1989) [34] assessment criteria in terms of water absorption. Chloride penetration results showed that the chloride permeabilities of all the concretes were below 1000 C, indicating that the concretes have very low chloride permeability as per ASTM C1202 [35] criteria. The highest total charge passed was 541 C for 85% fly ash RCC.

5. CONCLUSIONS

From the experimental work presented in this study that used very high volumes of fly ash, the following conclusions are made.

1. The study proved that it is possible to obtain workable (low vebe compaction time) RCC even at very low cement content with very high volumes of fly ash. For nearly same workable and fully compactable RCCs, increase in cementitious materials decreases required water to cementitious material ratio.
2. The mixes satisfied important requirement of RCC mix that is, good bond between the layers of the mixes even at very low cement content. Sufficient paste in the mixes resulted smooth surface finish and produced dense concrete mixes the plastic densities of the concretes was between 2275-2562kg/m^3.
3. Compressive strength of all the concretes increased with curing age. The study showed that the compressive strength development is higher in very high volume fly ash RCCs than high and moderate volume fly ash RCCs. After 90 days of curing, the 28 day compressive strength had exceeded by an average of 35, 32 and 25 percent for very high volume fly ash, high volume fly ash and moderate volume fly ash concretes of its 28 day compressive strengths respectively.
4. Strength of high fly ash RCCs is predominantly influenced by cement content than total cementitious material (cement and fly ash). Increase in cement content enhances both compressive strength and split tensile strength of RCCs. However, the improvement in splitting resistance is higher for very high volume fly ash RCCs and smaller for high volume and moderate volume fly ash RCCs than corresponding increases found for compressive strength.
5. The empirical relationship between splitting tensile strength and compressive strength is in good agreement with the empirical equation suggested by Raphael, 1984 for normal concrete.
6. The value of young's modulus of elasticity increases with strength and is in the range of 17 to 42GPa. The empirical relationship between static modulus of elasticity and compressive strength is moderately in agreement with equations suggested by ACI 318 and ACI 363R up to 35MPa compressive strength. However, the relationship shows higher modulus of elasticity values at compressive strengths higher than 35MPa.
7. The rebound hammer number increased with age and with increase in cement content. The rebound hammer number varied from 25 to 40 at 28 day curing for the concretes. The relationship between rebound hammer number and compressive strength of RCCs is overestimated at lower strengths and underestimated at higher strengths than normal concrete. The UPV values of RCCs varied from 3.57 to 4.55km/s.

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