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MIX DESIGN AND SOME MECHANICAL PROPERTIES OF HIGH PERFORMANCE CONCRETE

[1]DR. MAHESH M AWATI , [2]DR. R B KHADIRANAIKAR

[1]Tontadarya College of Engineering, Gadag
[2]Basaveshwar Engineering College, Baglkot

Abstract : *High performance concrete (HPC) is that concrete which meets special performance and uniformity requirements that cannot be always achieved by conventional materials, placing, and curing practices. This can be achieved only by controlling w/c ratio and addition of mineral as well as chemical admixtures. This study presents mix design of concrete in the range of 60 MPa to 120 MPa. The test program also includes determination of mechanical properties such as compressive strength, tensile strength, elastic modulus and Poison's ratio. The empirical equations are established and compared with some codes and with other researchers reported in the literature. As the study focuses on strength related properties durability aspect is not studied in the proposed research.*

Key words: high performance concrete, flexural strength, split tensile strength, elastic modulus, Poison's ratio

Introduction

Modulus of elasticity is a property that characterizes the elastic response of concrete. For the design of flexural members the modulus is important because it determines the contribution of the concrete to the flexural rigidity of the member. Apart from other materials that a have linear elastic curve, the concrete maintains a fairly non-linear behavior in the pre peak zone. This creates difficulties in defining the elastic modulus of the material. That is the reason why, we do not have generally accepted definition. Apparently the main controversies related to the percentage of the strength at which the modulus of elasticity must be calculated. ACI-318[4] considers the elastic modulus of concrete could be defined that has the gradient of the chord drawn between the origin and the point on the curve corresponding to 45 % of the average compressive strength of cylinders. Different researchers such as Shah and Ahmad[5], Hsu and Hsu[6] have used this value in their papers. A similar definition but with reference point at 40% of the strength is accepted by some standards (ASTM C469[7], Erocode-2[8], and Australian Standard AS 1012[9]) and by other authors such as Carrasquillo et al. [10], and Thoman and Raeder[11]. Some of the first to study the elastic modulus of high strength concrete, the definition was related with the slope of the tangent to the stress-strain curve at 25% of maximum stress. CEB-FIB[15] uses two slopes, one at origin and other at peak to describe the elastic properties of concrete. In addition Thorenfeldt and Tomasiewicz[16] proposed the slope of the chord at 60% of the peak as another elastic constant.

The following expression was proposed for the static modulus of elasticity of high strength concrete and is defined according to ASTM C469[7] at 40% of the ultimate load,

$$Ec = 3320\sqrt{f_c'} + 6900 \quad (\text{MPa}) \qquad \ldots (1)$$

The above equation is valid in the strength range of 21 & 83MPa. This equation attempted to correct the estimation of ACI-318[4], for normal strength concrete that had the following expression

$$Ec = 4730\sqrt{f_c'} \quad (\text{MPa}) \qquad \ldots (2)$$

In conclusion, though Young's modulus is a very important mechanical property, there are no accurate methods to determine its value for concrete, neither experimentally nor based on the compressive strength. Different methods of test and interpretation will give slightly different values. Obtaining the full stress-strain curve of the concrete in compression is a task that not every testing laboratory could achieve. Very stiff testing machines with a deformation-controlled loading system are required.

In the concrete structure, it is more likely that the tensile strength will be attained before the concrete fails in compression. Usually in design the value of the tensile strength is ignored, assuming that only the reinforcement will take all the tensile stresses. There are three methods to determine the tensile strength experimentally, uni-axial tension (direct tensile test), split tensile strength, and modulus of rupture. Direct tension is hard to achieve in practice, due to inevitable interaction between specimen and machine that tend to disturb the stress distribution. Splitting tensile strength is used in Europe. Legeron and Paultre[17] states that, even if a good correlation with direct tensile results were observed, the aggregates are usually fractured along the splitting plane, phenomenon unlikely to happen in direct tension, where they are pulled out. Modulus of rupture is regarded as the best to describe the flexural behavior of the members. Raphael[18] observed that the results are in a higher range than the last two by about 50%. The same author attributes this fact to the non linear nature of stress-strain diagram of concrete in tension, and to the inappropriate use of the elastic theory to derive the modulus of rupture. A co-efficient of 0.744 that has to affect the modulus of rupture in order to give the actual tensile stress was proposed after approximating the non-linear curve of concrete in tension with a rectangular stress-block.

Poisson's ratio is defined as ratio of lateral strain to the strain in the direction of loading. Poisson's ratios are in the range of 0.15 to 0.25. Concrete with higher strength would tend to have lower Poisson's ratio indicating the brittleness of higher strength concrete.

Research significance

Currently, HPC is widely used in bridges, buildings and other structures. However, design provisions for reinforced concrete members in current codes, such as the IS 456[21] are primarily based on empirical relationships for mechanical properties developed from testing normal strength concrete and the corresponding statistical parameters. This creates concern that the design may not be conservative when equations developed with NSC are applied to HPC. In contrast, the equations may be too conservative such that the advantages of using HPC are not fully realized. Thus, research is needed to determine statistically the significant relationship between the specified design compressive strength of HPC and splitting tensile strength f_{sp}, modulus of rupture f_r, and modulus of elasticity E_c.

Experimental Program

Mix Proportioning

Mix proportioning is the process of determining the right combination of component materials that will produce a concrete mixture with the desired characteristics at the lowest possible cost. Even with ordinary concrete the process is not easy because it involves the art of balancing various conflicting requirements. Extensive laboratory testing must often be carried out before a satisfactory proportion of materials are arrived at. Formulating high performance concrete is a more complex operation than formulating conventional concretes because the number of parameters to be managed is larger (up to three additional constituents). The critical point is often ”marrying” a cement and superplasticizer admixture in such a way that they produce a mixture that is fluid (despite a lower water content) and remains fluid long enough for easy placement of the concrete.

The processing operations can be arranged in the following series of steps.

1. It is necessary to choose the constituents, making use of available local materials.
2. One must then decide in what proportions the constituents of the concrete have chance of satisfying the specification.
3. The granular skeleton must be optimized by empirical or theoretical methods.
4. The binder(s) - admixture(s) system must be investigated.
5. Finally, it is necessary to test the rheological behavior of the concrete, then its mechanical characteristics.

Materials

Commercially available ordinary Portland cement of 53 grade (Ultratech cement) conforming to the relevant Indian standard code IS 12269[19] was used throughout the investigation. Crushed basalt stone aggregates were used in the present investigation. The maximum size of the aggregate was 20 mm to produce 60 MPa and 80 MPa and 12.5mm for 100 MPa and 120 MPa concrete respectively. Locally available sand quarried from Krisna River was used. The sand used conforms to grading zone II of IS 383[20]. Fly ash, silica fume (Elkem) and high range water-reducing admixtures (Glenium B233) were used to get required strength.

Design of HPC mixes

A mixture proportioning method only provides a starting mix design that will have to be modified to meet the desired concrete characteristics. In spite of the fact that mix proportioning is an art, it is unquestionable that some essential scientific principles can be used as a base for mix calculations.

Aitcin[25] proposed a simplified mixture proportioning procedure that is applicable for normal weight concrete with compressive strength values between 60 MPa and 120 MPa. The optimum volume of aggregate is suggested to be 65% of the volume of the high performance concrete. Concrete mix design for five target strengths was developed in line with the method suggested by Aitcin[21] as shown in Table 1.

Specimens

The desired compressive strength was found from the cubes (150 mm×150 mm×150 mm) and cylinders (150 mm×300 mm). Split tensile strength was obtained from cylindrical specimens of size 150 mm×300 mm. Flexural tensile strength was obtained from prisms of size 100 mm×100 mm×500 mm. The stress-strain relation and modulus of elasticity was studied by testing cylinders of size 150 mm×300 mm.

Mixing

As stated previously, HPC are produced in the same manner as of usual concretes, using the same production equipment, except that mixing sequence is usually longer. Obviously, all the equipment used to weigh and batch concrete ingredients must be accurate. Weighing devices must be calibrated regularly because it is essential that the carefully selected and controlled materials be weighed precisely in order to consistently obtain the targeted strength and workability. The HPC mixers are very sensitive to any variation in their proportions, especially in water content.

In this work concrete was mixed in a ribbon mixer of 250 kg capacity. About 70% of water was initially poured in the mixer followed by the other ingredients of concrete. Rest of water was added afterwards. The required quantity of superplasticizer was added with water. The mixer was rotated until homogeneous mix was obtained.

Instrumentation and test set up

The tests on cubes and cylinders were carried on a in a servo controlled compression testing machine of 3000 kN capacity. The flexural strength was evaluated in UTM. The LVDT's were attached on opposite face of a cylinder to observe the longitudinal deformations. 12 channel data logger was used to record load and displacement and was interfaced with a computer. The post peak response of stress-strain curves were not obtained due to explosive failure of cylinders. Top surface of cylinders were ground well before placing in the machine to ensure proper perpendicularity.

Results and discussions

The microstructure of HPC is more compact, including the transition zone with the coarse aggregate, resulting in a thin or no transition zone at all. Therefore, the mechanical properties of the coarse aggregate influence some of the mechanical properties of HPC. For any coarse aggregate there is a critical value of the water/binder ratio below which any further decrease of the water/binder ratio does not result in a significant increase of the compressive strength. This critical value depends on the strength of the rock from which the coarse aggregate is made, but also on the maximum size of the coarse aggregate. This is because when crushing a particular rock the smallest fragments are usually stronger than the coarsest because they content less defects. This phenomenon is sometimes referred as a 'size effect phenomenon'.

In broad terms, it can be said that usual concretes act as homogenous and isotropic materials in which the weakest link is the hydrated cement paste and /or the transition zone. On the other hand, HPC essentially act like a non- isotropic composite material made of hydrated cement paste and aggregates that can have quite different mechanical properties. Evidently the properties of this composite material are influenced by the properties of each of its constituents as well as water/binder ratio. The compressive test was carried out on specimens of cubical or cylindrical in shape and the test results are as given in Table 2.

Crack pattern

For a heterogeneous material like concrete, cracking is a dominant factor for its behavior, and the development of micro-cracking is closely related to the characteristics of the interfacial transition zone. The mode of failure of HPC specimens in uni-axial compression is different from that of NSC specimens because of improvement in the microstructure of concrete. The number and length of continuous crack pattern developed at failure decreases as the compressive strength increases. In-fact, the cracking of HPC is more localized and it approaches the behavior of a homogeneous material when compared with cracking in NSC. It is generally observed that the cracks develop between the interface of aggregate and the cement paste in NSC, on the other hand, in HPC, cracks propagate through the aggregate as well as paste and, consequently there is less resistance across crack surface due to reduced interlocking.

The mode of failure and cracking characteristics of both types of concrete specimens (Cubes and Cylinders) for different concrete strengths were observed during the test. In the case of cubes the fracture process is provoked by a stress concentration near the cube corners. Inclined micro-cracks appear and come together near the corners as shown in Fig. 1. As the load increases, the crushing leads to vertical cracks and column-like fragments as shown in Fig. 2. It had been observed that for NSC the first crack was seen at low stress level at around 40% of ultimate load. In HPC the first crack was produced at around 70%, the number of cracks increases on opposite faces at around 85% and ultimately the corners fail at around 95% stress level as shown in Fig. 1. In case of smaller specimens (100 mm×100 mm×100 mm) the cracking was same except that the first crack was produced at higher stress level, at around 75% leading to higher apparent strength of concrete. Finally the cubes crush down as shown in Fig. 3.

A simple visual inspection evidences that the extent of cracking throughout the specimen was denser in the cubes than in cylinders. A main inclined fracture surface was nucleated in cylinders as shown in Fig. 4 and they finally broke in all cylinders by a diagonal fracture plane as shown in Fig. 5. In the present study it was observed that the first crack in HPC cylinders was formed at around 85% of ultimate stress and on further loading the same crack propagates and initiating the failure with ultimately fewer numbers of cracks.

Tensile strength test

Concrete is relatively strong in compression and weak in tension. In reinforced concrete members, little dependence is placed on the tensile strength of concrete since reinforced bars are provided to resist all tensile forces. However, tensile stresses are likely to develop in concrete due to drying shrinkage, rusting of steel reinforcement, temperature gradients and many other reasons. Therefore, the knowledge of tensile strength of concrete is of importance.

Tensile strengths of concrete may be determined by the following two tests,

1. Split tensile strength test and
2. Flexure strength test

Split tensile strength.

It is also called as indirect tension test method. This also sometimes referred as, "Brazilian Test". This test was developed in Brazil in 1943. At about the same time this was also independently developed in Japan. This test is carried out by placing a cylindrical specimen horizontally between the loading surfaces of a compression testing machine and the load is applied until failure of the cylinder, along the vertical diameter. The test results are as given in Table 2.

The main advantage of this method is that the same type of specimen and the same testing machine as are used for the compression test can be employed. The splitting test is simple to perform and gives more uniform results than other tension tests. Strength determined in the splitting test is believed to be closer to the true tensile strength of concrete, than the modulus of rupture. An empirical relation is arrived for split tensile strength as given below and shown in Fig. 6.

$$f_t = 0.565\sqrt{f_c^{'}} \quad in\,MPa \qquad \ldots (3)$$

$$f_t = 0.536\sqrt{f_{cu}} \quad in\,MPa \qquad \ldots (4)$$

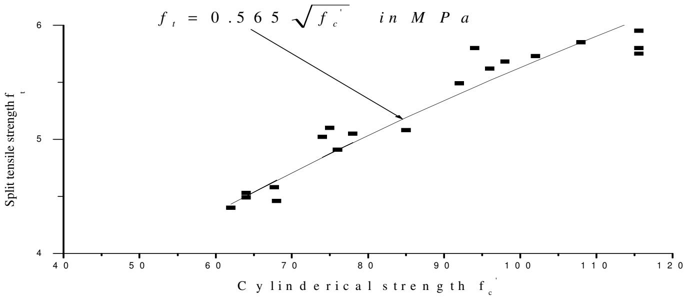

Fig. 6— Relation between split tensile strength and strength of concrete

The comparison of Eq. 3 may be made with the analytical equations proposed by ACI, Ahmed and Shah, Bhanja and Sengupta, Irvani Said, Mary Beth, and Salim Pul as shown in Fig. 7. The equation proposed by Salim Pul is only up to 80MPa strength of concrete. The proposed equation has good match with that of Bhanja and Sengupta (2005) and also very near to Said Irvani, ACI 318-98, and Mary Beth. However, the equations ACI 363R-84, Ahmed and Shah, and Salim Pul overestimates the splitting tensile strength.

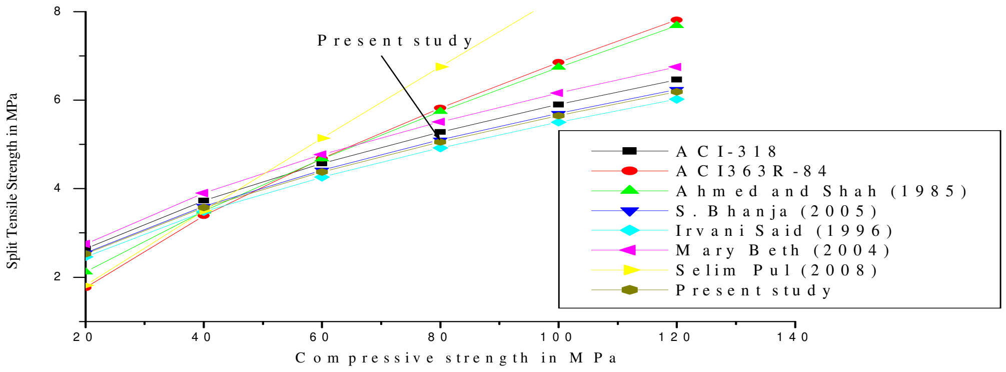

Fig. 7— Relationship of split tensile strength of the present work and other researchers

Modulus of rupture

The value of the modulus of rupture (extreme fibre stress in bending) depends on the dimension of the beam and the manner of loading. The systems of loading used in finding out the flexure tension are central point loading and third point loading; maximum fibre stress will come below the point of loading where the bending moment is maximum.

In case of symmetrical two point loading, the critical crack may appear at any section, not strong enough to resist the stress within the middle third, where the bending moment is maximum. It can be expected that the two point loading will yield a lower value of the modulus of rupture than the centre point loading. IS 516[26], specifies two point loading.

Results of flexural tensile strengths are shown in Table 2 and Fig. 8 and the relation for flexural strength are;

$$f_{r1} = 0.946\sqrt{f_c'} \quad in\, MPa \qquad \ldots (5)$$

$$f_{r2} = 0.90\sqrt{f_{cu}} \quad in\, MPa \qquad (6)$$

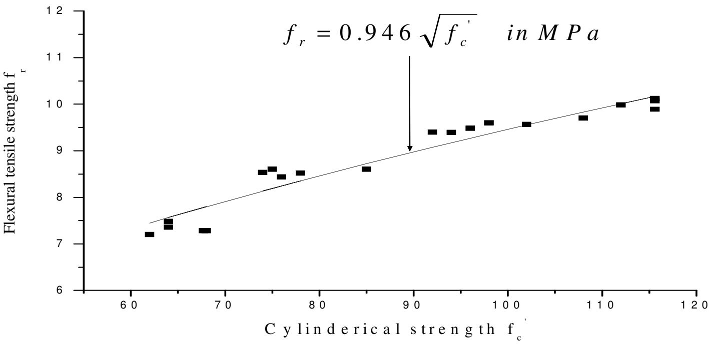

Fig. 8— Relation between strength of concrete and flexure tensile strength

The comparison of present data with the Eq.5 may be made with the analytical equations available in the literature as shown in Fig. 9. The comparison of flexural strength of high strength concrete is made with the equations available in the literature such as equations proposed by Ping Kon, S. Bhanja, Irvani Said, Mary Beth, and Selim Pul. The proposed equation is in complete agreement with ACI 363 R-84 and is close to equation proposed by Irvani Said. The equation of Ping Kon and Mary Beth under estimates the modulus of rupture. Equation proposed by S. Bhanja under estimates flexure tensile strength at lower strength levels and overestimates at higher strength levels.

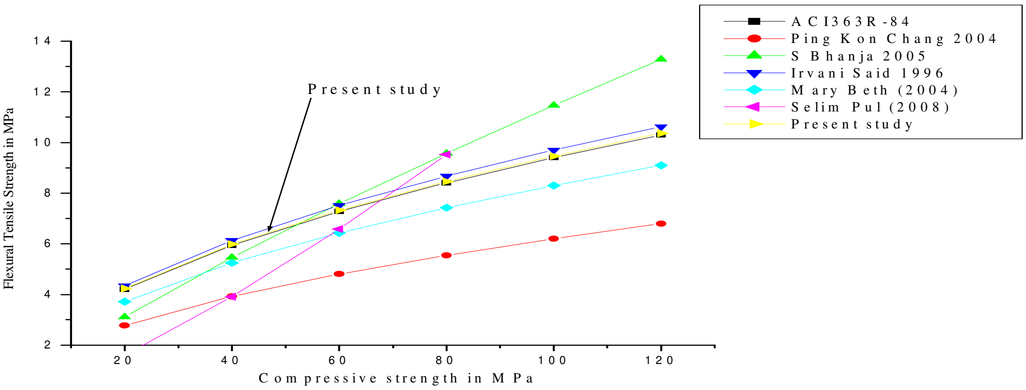

Fig 9 Analytical equations for Flexure tensile strength

Modulus of elasticity of concrete

From the stress-strain curves generated in the study as shown in Fig. 10, for various grades of concrete, elastic moduli at 40% stress level is evaluated and are given in Table 2. The elastic modulus E_c, for each specimen is plotted as a function of concrete strength f_c', as shown in Fig. 11. Since concrete strength strongly influences the modulus of elasticity there have been many attempts to formulate the relation between two. Fig. 11 contains the 211 data of others in the literature, namely, 39 data of Wee (40 MPa to 125 MPa), 48 of Gesoglu (60 MPa to

100 MPa), 37 data of Ozuturan(14 MPa to 47 MPa), 36 of Turan data (20 MPa to 30 MPa), 25 of Said Irvani (60 MPa to 120 MPa), and 5 data of Pornchai (35 MPa to 75 MPa). The strengths mentioned in the bracket indicate the range of concrete strength a researcher had studied. Fig 11 also consists of 20 data of present research for strength in the range of 60 MPa to 115 MPa. Regression analysis of the present data indicates the relation for E_c as shown below;

$$E_{C1} = 5050\sqrt{f_c^{'}} \quad in\, MPa \qquad \ldots (7)$$

$$E_{C2} = 4800\sqrt{f_{cu}} \quad in\, MPa \qquad \ldots (8)$$

The values of E_c obtained in the present research are in the range of 40 to 56 GPa for the strength in the range of 60 to 120MPa. Some of the equations proposed by codes and researchers are as shown in Table 3.

The values of Ec obtained in the present research are in the range of 40 to 56 GPa for the strength in the range of 60 to 120 MPa.

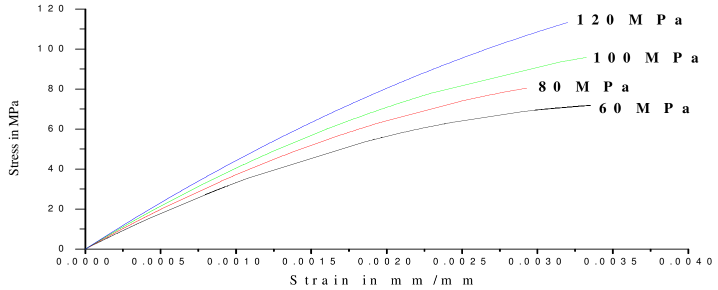

Fig. 10— Typical ascending branches of stress-strain relationships of strength 60-120 MPa

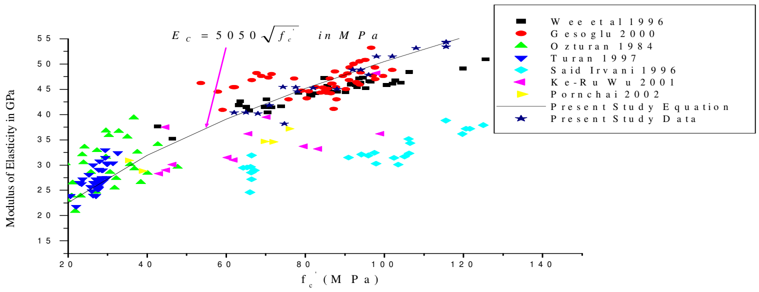

Fig. 11— Values of elastic modulus of present research and others in the literature

Poisson's ratio

Poisson's ratios have been evaluated by testing the cubes in the absence of fixing attachment of displacement transducer along lateral direction. The test set is as shown in the figure. At higher stress levels micro cracking starts to develop parallel to the direction of stress. Because of this transverse strain increases at higher stresses. Close to ultimate strength Poisson's ratio increases rapidly until failure occurs. Due to this reason the Poisson's ratio is determined at 40% level of axial stress, that is, the point corresponding to which elastic modulus is determined. The results of the present study are as given in Table 2. The Poisson's ratios of 120MPa concrete were not determined due to difficulty of instrumentation to the specimen of size 100 mm×100 mm×100 mm, in the limited availability of pi-gauges of 50mm gauge length. The average values of Poisson's ratio are 0.175, 0.166 and 0.153 for 60MPa, 80MPa and 100MPa strength of concrete respectively. The results of present study and of others such as Carrasquillo[09], Said Irvani[30] Pornchai[32] and Metrol[33] are represented in the Fig. 12. The figure indicates there is no clear trend for Poisson's ratio, however, the present study indicate decrease in the average value of Poisson's ratio as strength increases.

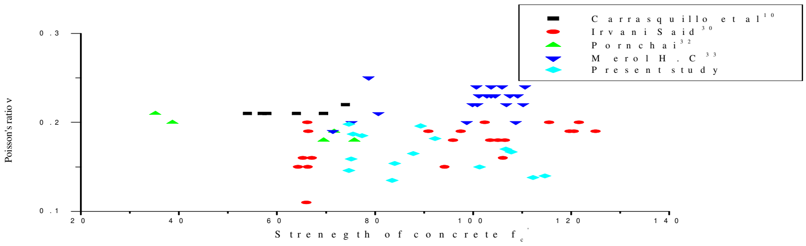

Fig. 12— Variation of Poisson's ratio with strength of concrete

Conclusions

In the proposed study mix design of high performance concrete from 60MPa to 120MPa concrete is carried out and then the mechanical properties are studied such as compressive strength, split tensile strength, flexure tensile strength, elastic modulus and Poisson's ratio and the following conclusions are drawn.

1. The proposed mix design method is effective in producing HPC of required strength effectively and economically and the method is simple to adopt.
2. The split tensile strength and flexural strength are related to the compressive strength of concrete and are in good agreement with ACI and the equations proposed by Irvani Said[30], which are applicable up to 120 MPa the strength.
3. Elastic modulus determined in the proposed study is compared with others and found the equation proposed is nearly same as that of Mary Beth.
4. The average Poisson's ratio is 0.165 which is generally acceptable (0.15 -0.25).

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Table 1— Mix proportioning for five target compressive strengths

Materials	**Target Compressive strengths in MPa**				
	40	**60**	**80**	**100**	**120**
Water cement ratio	0.50	0.35	0.30	0.25	0.23
Cement, kg/m^3	350	366	414	440	550
Fine aggregate, kg/m^3	850	692	659	672	620
Coarse Aggregate, kg/m^3	1100	1100	1100	1100	1085
Water, kg/m^3	175	160	155	137.5	144
Fly ash, kg/m^3	-	91	103	69	30
Silica Fume, kg/m^3	-	-	-	41	45
High range water reducers Glenium B233 in %	-	0.4	0.4	0.6	1.00
28-days Compressive strength					
Cube compressive strength, MPa	54	76.44	93.33	112	122
Cylinder compressive strength, MPa	44.80	63.00	76.90	95.6	115.6

Table 2— Test results of tensile strength of concrete

Grade of Concrete in MPa	Cube Strength f_{cu} in N/mm^2	Cylindrical Strength $f_c^{'}$ in N/mm^2	Split Tensile Strength f_t in N/mm^2	Flexural Strength f_r in N/mm^2	Elastic Modulus $E_c$in GPa	Ultimate Strain in mm/mm	Poisson's Ratio
60	75.55	62.00	4.40	7.20	40.40	0.0023	0.187
60	74.66	64.00	4.49	7.48	41.84	0.0028	0.198
60	75.11	67.71	4.58	7.28	40.20	0.0027	0.159
60	74.66	68.00	4.46	7.28	40.43	0.0026	0.146
60	77.33	65.00	4.53	7.46	38.18	0.0024	0.185
80	83.50	76.00	4.91	8.44	45.42	0.0030	0.135
80	84.00	78.00	5.05	8.52	45.05	0.0026	0.154
80	92.22	85.00	5.10	8.60	45.47	0.0027	0.182
80	89.33	75.00	5.02	8.53	44.61	0.0030	0.196
80	87.77	74.00	5.08	8.60	45.27	0.0029	0.165
100	101.33	92.00	5.49	9.40	47.88	0.0028	0.150
100	107.77	94.00	5.80	9.39	51.52	0.0027	0.167
100	106.67	96.00	5.62	9.48	48.87	0.0029	0.170
100	112.22	98.00	5.68	9.60	51.52	0.0030	0.138
100	114.67	102.00	5.73	9.56	48.87	0.0031	0.140
120	121.33	108.00	5.85	9.70	53.16	0.0032	-
120	118.00	112.60	5.95	9.89	54.28	0.0029	-
120	112.00	105.60	5.75	10.07	56.58	0.00325	-
120	122.00	115.60	5.80	10.12	54.37	0.0028	-
120	118.00	108.00	5.89	9.98	53.43	0.00315	-

Table 3. Equations for modulus of elasticity by codes and researchers

Sr. No.	Researchers Name/ Code	Equation suggested
01	Euro Code 2	$E_c = 21500\left[\frac{f_c^{'}}{10}\right]^{\frac{1}{3}}$
02	Gardener (2000)	$E_c = 3500 + 4300\sqrt{f_c{'}}$
03	Mokhtr zaden & Frech	$E_c = 3320\sqrt{f_c^{'}} + 6900$

Sr. No.	Researchers Name/ Code	Equation suggested
04	ACI 363-94	$E_c = 6900 + 3300\sqrt{f_c'}$ 21 MPa< f_c'< 83MPa
05	CSAA23.3-94	$E_c = 5050\sqrt{f_c'}$
06	Mary Beth D. Hueste(2004)	$E_c = 5230\sqrt{f_c'}$ 40MPa< f_c'<90MPa
07	IS 456-2000	$E_c = 5000\sqrt{f_{ck}}$ f_{ck} is characteristic strength of concrete

Fig. 7.1 Coalescence of cracks near the corners

Fig. 7.2 Vertical Cracks leading to Column fragments

Fig. 7.3 Ultimate Cracking pattern of Cubes

Fig. 7.4 Nucleation of inclined fracture surface and diagonal fracture zone

Fig. 7.5. Ultimate Cracking pattern of cylinders