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Research Paper

Evaluation of mechanical properties of concrete for its sustainable development

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The built environment is a major contributor to CO_2 emissions accounting for approximately 50% of global emissions. To reduce impact, all aspects of construction practices need to be investigated. In this paper the attempt was made to investigate the feasibility of use of packing density method for design of concrete mix rather than traditional methods of concrete mix. The water-cement ratio was kept 0.45 for all the mixes. The mechanical properties of concrete such as compressive strength, permeability, abrasion, water absorption and ultrasonic pulse velocity were evaluated. The test results revealed that, the compressive strength was comparable to that of control concrete. On the other hand, durability parameters had shown remarkable improvement. The permeability reduced by 8.5 % and the water absorption of concrete reduced by 44% in comparison to concrete designed by conventional IS code method. Resistance to abrasion also increased by 19% as compared to control concrete. The cement content could be saved by 22% by packing density approach with desired workability and strength. The concrete prepared with packing density approach was found out to be of better quality, cost effective and sustainable.

1 Introduction

Sustainability is a key focus in construction and the materials used are examined using a broader scope that addresses the full life cycle of the product. The main motivation for industrial change is to reach carbon emission targets by 2050 [1]. As a central material for infrastructure in the built environment, concrete is increasingly investigated to evaluate and address issues of sustainability. The energy consumed by the operation and maintenance of a building accounts for 80-90% of the embodied energy, therefore the embodied energy of concrete is typically neglected [2]. While the embodied energy of concrete per kilogram is low, it is typically used in large quantities, which leads to considerable environmental impact, mainly from cement [2].

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Concrete is the most widely used and important construction material in the world. Cement is the primary component of concrete and the energy used in manufacturing accounts for approximately 98% of the embodied energy, approximately 3.9 GJ per ton [3]. Drastic changes are needed if we are to meet our 2050 emissions targets [4].There are various methods available for design of concrete mixes. In general practice the concrete mixes are designed by using given standards. The aggregates and cement are tested in labs and with the help of data available in the codes for the design of mixes. While designing the concrete mix by packing density approach more emphasis is given on the combination of aggregates i.e. coarse and fine aggregates. The coarse aggregate and fine aggregate are mixed in different proportions to arrive at maximum packing density and minimum void content. The cement paste is added in the selected mixture of aggregates to achieve desired workability and strength.

Approximately 75% constituents of concrete consist of coarse and fine aggregates. In the design of concrete mix by packing density approach the quantity of aggregate (coarse and fine) increases when compared to the conventional method of mix design. The increase in packing density and reduced voids content in the aggregate mixture results in reduced amount of binder required to give the desired strength of concrete mix. With excessive aggregate the concrete mix becomes stiff and hence desired workability is not achieved. Therefore, super plasticizers are required to be added in the mix to attain desired slump. Another benefit of packing density approach is the reduction in cement content in concrete which results in reduced emission of carbon di oxide in the atmosphere. Overall the concrete becomes cost effective and sustainable.

In a study by Bhattacharjee et al. [5], the compressive strength obtained by packing density approach are comparable to that of BIS code method for a given water-cement ratio. They had developed co-relation curves between compressive strength and waster-cement ratio and compressive strength vs cement paste content. Theses curves were used to decide the water-cement ratio and paste content for specified grade of concrete in packing density method. Fennis et al. [6], in their study reported that concrete mixes can be designed by using particle packing method and it is possible to reduce the cement content up to 50% and the CO_2 emission can be reduced by 25%. Another study carried out by Jeenu et al. [7], the packing density was measured by using seven types of fractions of aggregate with four different series of mixes. A generalized empirical equation for obtaining an effective particle size distribution of aggregates for optimal performance of concrete was proposed. By using this equation the gradation curve was plotted, the packing density and compressive strength was found to be maximum as compared to the standard gradation curves. Kwan & Wong [8] reported that, the packing density of concrete mix with pulverized fuel ash, and condensed silica fume increases with use of third generation poly-carboxylate based super plasticizers. He also reported that, the use of cement in the range of 15% to 20% by volume in concrete mixes gives minimum void content.

Research has been also carried out by using alternative cementitious materials in concrete mixes [9] and mechanical properties like compressive strength and workability have been studied. But no literature has been traced reporting durability properties of concrete mixes designed by packing density approach. In the present study attempt has been made to study strength properties and durability parameters like permeability, water absorption, resistance to abrasion etc. of the concrete designed by packing density approach.

2 Materials and Methods

2.1 Characterization of Materials

Portland Pozzolana cement used in this study fulfils the requirement of BIS: 1489-part 1 [10]. The initial and final setting time, consistency and compressive strength of cement are shown in Table 1. Sand was collected from Banas River, Rajasthan. The sand used in this study conforms to grading zone II of BIS: 383-1997 [11].The proportion of sand are presented in Table 2. The coarse aggregate used in this study confirms to BIS: 383-1997 [11]. The Specific gravity and water absorption of coarse aggregate are presented in Table 2. The nominal maximum size of coarse aggregate used.

To achieve the desired slump of 75 mm, a third generation poly-carboxylate based super-plasticizer Rheobuild 522 ND conforming to BIS: 9103-1999 [12] was used.

Table 1- Physical properties of cement

Initial Setting Time	47 minute
Final setting time	483 minute
Compressive strength	
3 days	20MPa
7 days	24MPa
28 days	39MPa
consistency	27%
Specific gravity	3.11

Table 2- Physical Properties of Aggregates

Aggregate Type	Specific gravity	Water Absorption (%) by weight	Grading Zone
Coarse aggregate	2.61	0.54	As per Table 2 of BIS 383
Fine Aggregate	2.66	2.0	Zone II As per Table 4 of BIS 383

Table 3- Particle size distribution of coarse aggregate

Sieve size(mm)	Percentage Passing of Natural Aggregate
40	100
20	95
10	55
4.75	6.8

2.2 Concrete Mix Proportioning

For the design of concrete mix by packing density approach various formulations of aggregate fractions were prepared. Firstly two size fractions of coarse aggregate 20 mm and 10 mm were mixed in a definite proportion by weight, such as 90:10, 80:20, 70:30 and 60:40, etc., and the bulk density of each mixture was determined. However, a stage was reached when the bulk density of the coarse aggregate mixture, instead of increasing, decreases again. The mixture giving highest bulk density was mixed with fine aggregate in the ratio of 90: 10, 80: 20, 70: 30, 60: 40, 50: 50, etc. By increasing the finer content, the bulk density increases up to a peak value after which it again reduces. Thus, the proportion obtained for maximum bulk density was fixed for total aggregates, i.e., coarse aggregates 20 mm: coarse aggregates 10 mm: fine aggregates were 36: 24: 40 by weight. The bulk density, packing density and voids contents are plotted against the weight fraction of all in aggregate are presented in the Figure1, Figure 2 and Figure 3, respectively.

After getting all the values of bulk density, packing density and void contents the mix proportion of concrete were calculated. The concrete mix was prepared by taking cement paste content 0%, 5%, 10%, 15% and 20% in excess of void content in the aggregate mix. The mix proportions by both approaches are given in Table 5. All the concrete mixes were prepared by using a constant water-cement ratio of 0.45. Before the addition of water, the dry concrete mixes were blended for 5 minutes to achieve a thorough mix in a 160 lit capacity mixer.

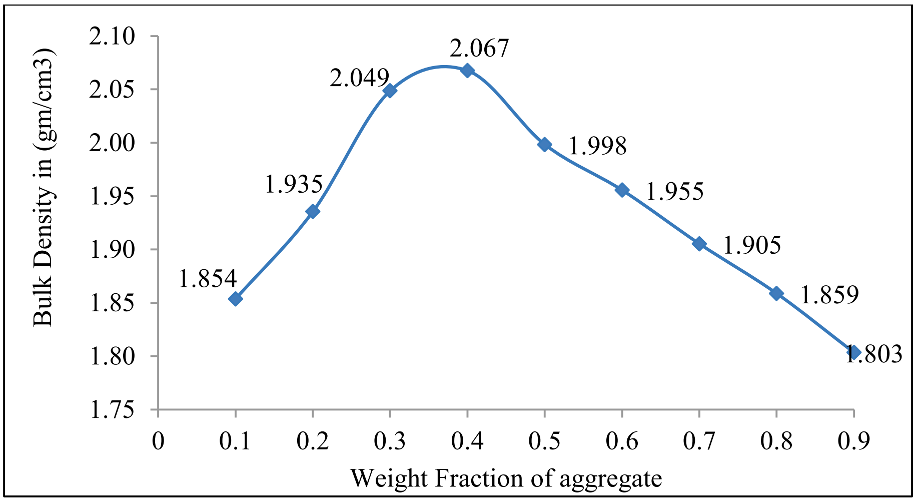

Figure 1- Bulk Density of all in aggregate

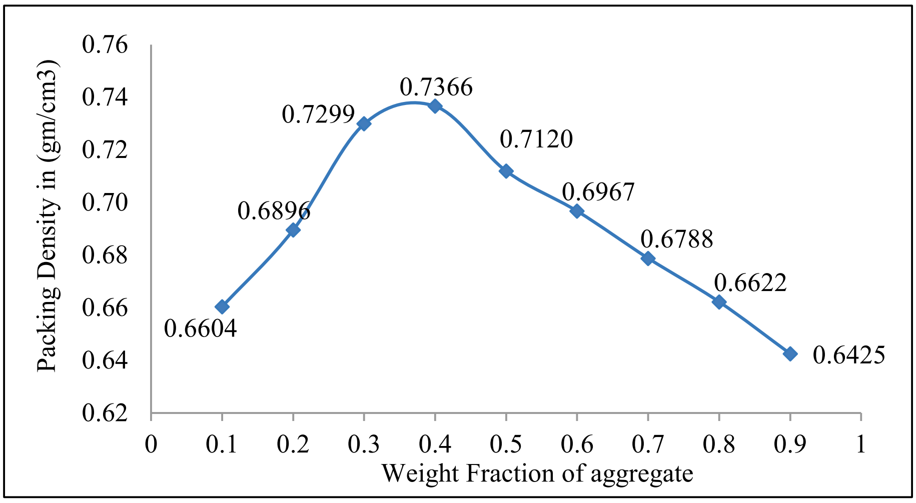

Figure 2- Packing Density of all in aggregate

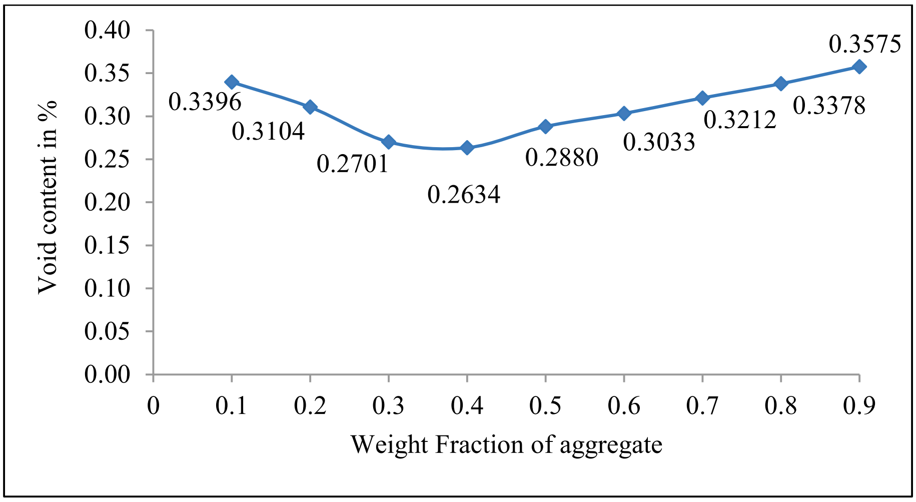

Figure 3- Void content of all in aggregate

Table 5- Mix Proportion

Mix	Paste content in excess of voids (%)	Water (lit.)	cement (kg)	sand (kg)	Coarse Aggregate (kg)	
					20 mm	10 mm
C 1	-	192	426	663	531	649
C 2	10	157	348	800	720	480

***Note**: Mix designated by C1 shows control mix designed as per BIS 10262-2009 and mix designated by C2 shows mix designed by Packing Density approach.*

2.3 Sample preparation and test methods

The ingredients of concrete were mixed in a mixer and cubes of size 150 mm × 150 mm ×150 mm were cast for determining the compressive strength and permeability of test specimens. All the specimens were de-moulded at the age of 24 ± 1 h and thereafter were cured in water tank at room temperature up to the specified age of test.The slump cone test on freshly prepared concrete mix was carried out as per BIS- 1199-1999 [13]for measuring workability of concrete. Compressive strength of concrete specimens was determined at 7 days and 28 days curing age as per BIS: 516-1959 [14]. To assess the porosity in concrete, water permeability test was conducted as per German standard DIN -1048 part 5 [15].Test specimens100 mm × 100 mm ×100 mmcubes were cast for determination of water absorption test. This test was conducted according to BIS 15658:2006 [16].In order to assess homogeneity and quality of concrete the ultra-sonic pulse velocity test was conducted according to BIS 13311(Part 1) [17]. The dynamic young's modulus of elasticity of concrete specimens was determined according the BIS 13311(Part 1) [17].Abrasion resistance was measured in terms of depth of wear of concrete under standard testing conditions. It was performed according to BIS 1237:2001 [18]on test specimens of 100 mm concrete cubes. For an each test minimum three specimens were cast and tested.

Figure 4- Casting and curing of specimen's

3 Results and Discussion

3.1 Workability

The results of the slump values are presented in Table 6.

Table 6- Workability of concrete Mixes

Mix	Excess Paste content (%)	Dose of super plasticizer(%) by weight of cement	Slump (mm)
C1	-	0.25	78
C2	10	0.90	90

It can be seen that, the amount of super plasticizer required for achieving the desired slump was more in case of packing density method as compared to that of BIS code method. This is because sand content in mix C2 absorbs more water resulting in stiff mix. Hence higher dose of super plasticizer is required in C2 mix to achieve desired workability.

3.2 Density of Concrete

The variation in density of hardened concrete specimens can be seen in Figure 5.

It was observed that, the density of the concrete mix increases from 2307 Kg/m^3 to 2377 Kg/m^3. The density of concrete depends upon volume fractions of constituent materials and their densities, and the volume of voids present in the concrete. Concrete density is inversely proportional to its porosity. Due to improved packing of particles in concrete mix C2 the porosity of concrete decreases and hence density increases by 3%.

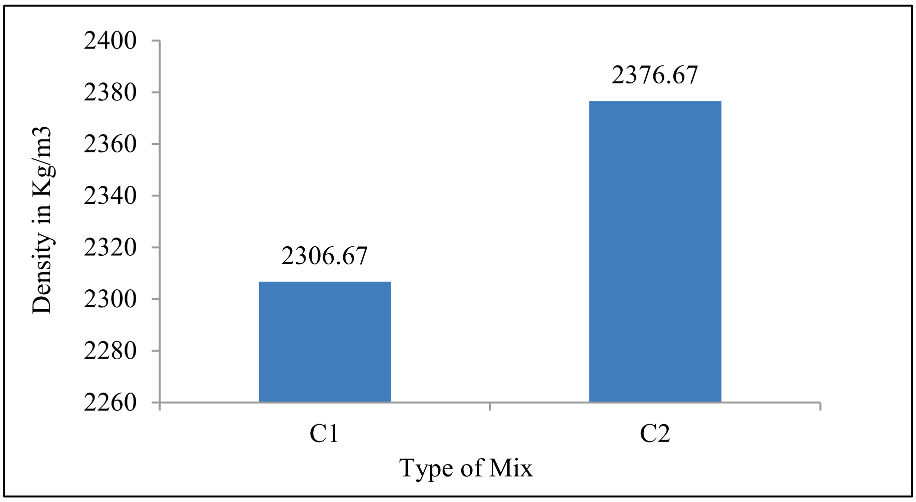

Figure 5- Density of concrete mix

3.3 Water Absorption and Permeability

The variations in water absorption of concrete specimens are given in Figure 6.It can be seen that the water absorption of concrete mix C2 reduced by 44.53% as compared to that of concrete mix C1. It means that the pores in the concrete mix were filled up by the cement paste and aggregate particles. Due to higher packing of particles the pores in the concrete mix reduced. This reduction in the pore space in concrete mix resulted in a reduction of water absorption of the test specimens.

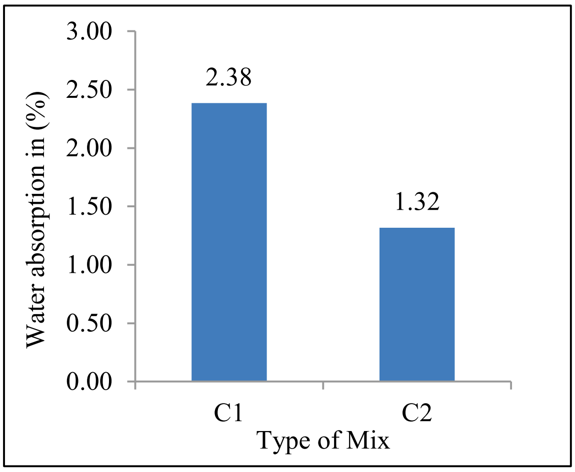

Figure 6- Variation in Water Absorption of concrete

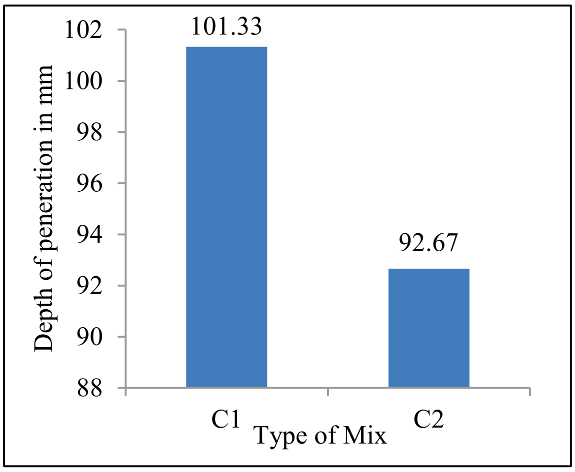

Figure 7- Variation in Water Permeability of concrete

The variations in the depth of water penetration in concrete specimens are shown in Figure7.

From the figure, it can be seen that the depth of penetration of water of concrete mix C2 was reduced by 8.5% as compared to that of concrete mix C1. The permeability of concrete depends on various factors; one of the major factors is the interconnectivity of pores in the concrete. These results show that the interconnectivity of pores in concrete mix C2 was less as compared to that of concrete mix C1. Due to coating of cement paste on surface of aggregate particles the lubrication improves, thus resulting in filling of pores by finer fraction. Remarkable improvement in water absorption and permeability is likely to improve resistance against corrosion and carbonation in concrete designed by packing density approach.

3.4 Compressive strength

The results of variation in the compressive strength of concrete are shown in Figure 8.

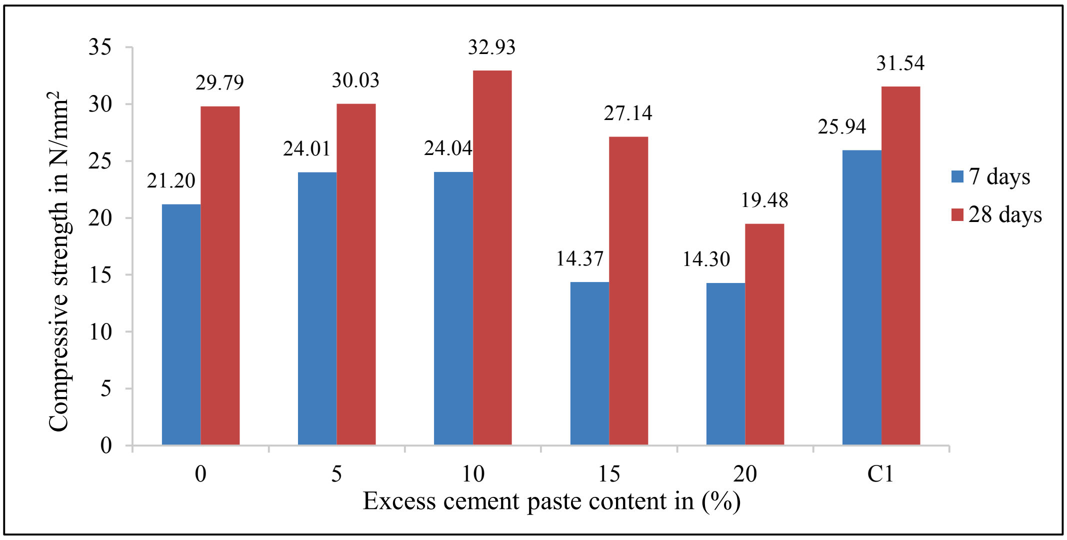

Figure 8 Variation in compressive strength of concrete

It can be seen that, the compressive strength of the concrete mix designed by packing density method increases up to 10% excess cement paste. The cement paste has first to fill up the voids between aggregate particles and the excess paste content is utilized to disperse the aggregate particles to produce a thin coating of paste surrounding each aggregate particle for lubricating the concrete mix [16].This excess paste strengthens the bond between the aggregate particles. Higher packing of aggregate leaves less space for voids hence increases the strength of concrete mixtures. The highest value of compressive strength was obtained in 10% excess paste content and almost equal to that of concrete mix designed by BIS code method. This was due to enhanced packing of particles in the concrete mix. At 15% and 20% excess cement paste, the strength decreased by 17.58% and 40%, respectively. The reduction of compressive strength at higher cement paste content is attributed to thick layer of paste around aggregate particles, resulting quick failure of bond. Such poor cohesion results in poor strength. Control mix C1 designed as per BIS 10262-2009 and achieved the target mean strength. The compressive strength at 10% excess cement paste is almost equal to that of control concrete mix. This is a remarkable improvement in the strength property of concrete designed by packing density approach.

3.5 Ultrasonic Pulse Velocity

The variations in ultrasonic pulse velocity values are shown Figure 9. From the Figure it can be seen that, the pulse velocity through the concrete mix increased as the method for the design of concrete mix was changed to packing density approach. The values of pulse velocity of concrete mix increases from 4.462 m/s to 5.238 m/s. This increase in pulse velocity values was due to denser packing of the particles in the concrete mix C2. Higher values of pulse velocities obtained in this study indicate, better quality in terms of density, homogeneity and uniformity was good as compared to that designed by BIS code method.

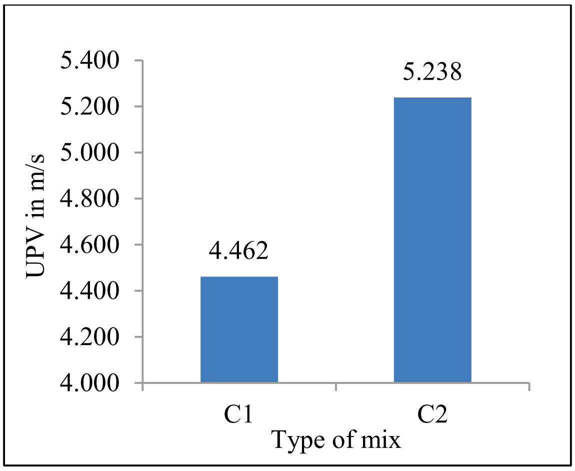

Figure 9- Variation in Ultra sonic Pulse Velocity of concrete mix

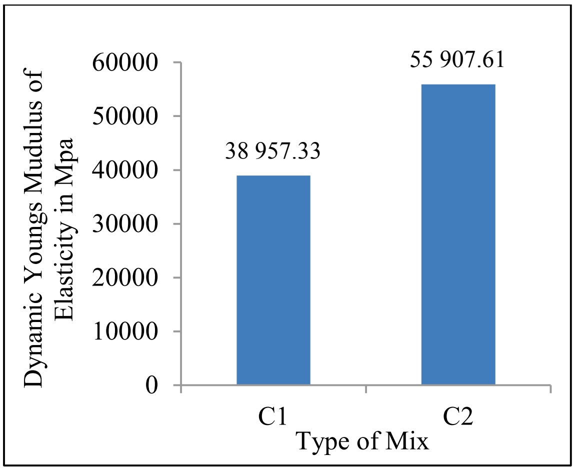

Figure 10- Dynamic Young's Modulus of Elasticity of concrete mix

3.6 Dynamic Young's Modulus of elasticity (E)

The results of the dynamic young's modulus of elasticity of concrete are presented in Figure 10.

The dynamic young's modulus of elasticity is a material property that describes its stiffness. From the results it is observed that, the value of E in concrete mix C2 is 43% more than that of mix C1. This increase in the value of E of mix C2, was due to the denser packing of particles and stiff matrix of the materials.

3.7 Abrasion resistance

The abrasion resistance was measured in terms of depth of wear of concrete specimens. The results of variation in average depth of wear on the concrete mixes are shown in Figure 11.

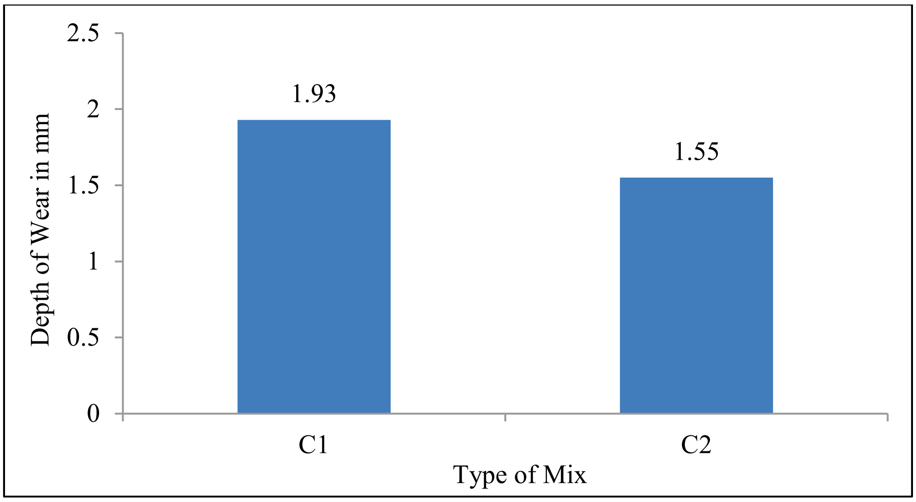

Figure 11- Variation in Abrasion resistance of concrete

It can be seen that, the depth of wear of concrete mix C1 was 19.69% more than that of concrete mixes C2. This reduction in depth of wear in concrete mix C2 was due to dense packing of particles. Due to dense packing of particles and excess cement paste, the bond between aggregates and cement paste become strong. As the bond between the particles was good, these particles cannot be separated by the external forces acting on the surface of the concrete. As per the BIS code, the average maximum wear shall not exceed 3.5 mm and wear on any individual specimen shall not exceed 4 mm in general purpose tiles. For heavy-duty floors, it is 2 mm and 2.5 mm, respectively. The results obtained in this test revealed that both the concrete mixes are within the permissible limits specified by the code and can be used for heavy duty flooring tiles. However, it would be much safer to follow packing density approach to offer higher resistance to abrasion.

3.8 Cost analysis and CO_2 emission

While deigning the concrete mixes by adopting any methodology production cost is one of the most important factors. The cost analysis of the concrete mixes designed by both the methods is given in Table 7.

Table 7- Cost for production of 1m^3 of concrete

Mix	Water	Cement	Sand	Natural Aggregate	Production cost (Rs.)
C1	-	2386/-	355/-	479/-	3220/-
C2	-	1949/-	425/-	488/-	2862/-

From the Table it was observed that, change in design approach for concrete mix reduced the cement consumption by approximately 22% as compared to that of control mix. The concrete mix designed by packing density approach resulted in saving in 13% saving production cost of concrete mix.

One of the major contributors for CO_2 emission in the world is cement industry. Annually cement industry contributes for greenhouse gas emission is 3.95 billion tons of [19]. In India around 275 MT of cement was produced during the year 2014 which account for generation of equal amount of CO_2 [20], [21]. For the production of 1Ton of cement around 0.94 Ton of CO_2 is released [22]. The CO_2 emission factor for road transport, i.e. truck or lorries is considered as 512.2 g/km [23].

Table 8- Reduction in Carbon dioxide Emission

Mix	Cement (Kg/m^3)	CO_2 emission (Kg/m^3)	Percentage reduction in CO_2 emission (Kg/m^3)
C1	426	401	-
C2	348	327	22.63%

From the Table 8 it can be observed that, the quantity of cement required for design of concrete mix C2 reduced by 22% which resulted in approximately 23% lesser emission of carbon di oxide. Implementing the concept of packing density method for design of concrete mixes reduces the annual global cement production from 4.2 billion tons to 3.36 billion tons which consequently reduces the CO_2 emission from 3.95 billion tons to 3.16 billion tons. Hence the concrete produced by adopting packing density method for design of concrete mixes is not only cost effective but also suitable product mitigating environmental pollution to large extent.

4 Conclusion

Concrete is consumed globally and demand is increasing with growth in developing countries. The primary constituent of concrete, cement, has a significant impact on the environment. Cement manufacturing is an energy intensive process that consumes significant amounts of raw materials and emits large amounts of CO_2. Reducing the impact of cement focuses on substitution of non-renewable fuels, development of supplementary cementitious materials and change in the design approach. The concrete mix designed by packing density approach needs some trials for determination of maximum packing density of given sample of coarse and fine aggregate. This minor exercise results in improvement of durability properties of concrete without affecting strength. The product also proves to be cost effective due to saving in cement.

Based on the study following conclusions have been drawn.

- Compressive strength and workability of concrete mix designed by packing density approach are comparable to those of control concrete at same water-cement ratio.
- Water absorption was drastically reduced by 44% as compared with that of control concrete. This is a favorable point indicating reduction in possibility of corrosion in reinforcement.
- Reduction in permeability by approx. 10% compared to control concrete is also indication of enhanced durability related to carbonation.
- Resistance to abrasion was also increased by 25% as compared with control concrete.
- The concrete designed by packing density approach was found to be homogeneous and well compact in structure.
- The use of packing density approach for design of concrete mixes results in 22% saving in cement consumption and 13% overall production cost of the concrete.

Overall the study depicts that, the use of packing density approach for design of concrete mixes would be economical and sustainable product. Above mentioned results give clear indication to follow packing density approach in concrete mix design.

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