EFFECT OF COARSE AGGREGATE GRADING ON THE FRESH AND HARDENED PROPERTIES OF HIGH STRENGTH CONCRETE

	**Mr. R. Selvam** holds a Master’s degree in business management from Alagappa University, Karaikudi. He has published six papers in national journals. He is the QA/QC Manager (concrete division) at the LTCRTC, Chennai. He has 20 years’ experience in working with building materials and served as a Quality Manager in seven Ready Mix Concrete plants situated in Chennai. His areas of interest are the development of alternate cements, non-destructive assessment of concrete structures and real concrete quality assessment. E-mail ID: rse@lntecc.com Mobile: +91 944 541 2467
	**Dr. Murugan Muthu** holds a PhD from Indian Institute of Technology Madras, Chennai. He is the R&D Manager (concrete division) at the L&T Construction Research and Testing Center (LTCRTC), Chennai. He has published six papers in peer-reviewed international journals and attended two international conferences. His areas of interest include characterisation of construction materials, new product development and durability assessment of concrete structures. E-Mail ID: mnmuthu@lntecc.com Mobile: +91 996 266 1506
	**Mr. Mocharla Indrakiran Reddy** hold a B. Tech. degree in Civil Engineering from the NBKR Institute of Science and Technology, Nellore. He is the Senior Engineer (concrete division) at the LTCRTC, Chennai. His areas of interest include concrete mix optimisation, light weight concrete and project management. E-mail ID: INDRAKIRAN@lntecc.com Mobile: +91 910 032 2111
	**Dr. V. Govindaraj** is having about 25 years of blended experience in academic, design and research in structural engineering. His area of research includes structural optimization, seismic design, precast structural connections, and structural concrete. He is currently heading the LTCRTC at Chennai. He has about 15 papers to his credit in the peer reviewed international journals and conferences. E-Mail ID: vgr@lntecc.com Mobile: +91 944 500 6297

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R. Selvam*, Murugan Muthu, Mocharla Indrakiran Reddy, and V. Govindaraj

L&T Construction Research and Testing Center, Manapakkam, Chennai 600089

ABSTRACT

This study investigated the packing effects of coarse aggregate on the fresh and hardened properties of high strength concrete (HSC). Five types of coarse aggregate packing were considered as the major parameter to validate the HSC properties like hydration, slump, air content, mechanical strengths, and chloride ions penetration depth. Such test results indicate that the denser the aggregate packing the better the workability, engineering and permeation properties under the enough paste content. Particularly, the HSC blended with same amounts of 20 mm and 10 mm sized coarse aggregates showed an improved performance than the HSC mixtures proportioned with single-sized aggregates.

Keywords: High strength concrete; aggregate gradation; hydration; workability; mechanical and durability properties

1. INTRODUCTION

In recent times, ready mix concrete (RMC) is often preferred by the Indian construction industry to build residential and commercial buildings, airports, runways, ports, energy generation facilities, production plants, and roads. Achieving a robust high strength concrete (HSC) mix from the Indian RMC plants at large scale is still a great challenge. Several researchers are constantly working on the optimisation of HSC mixture to deliver a high-quality product for site applications. The major factors to be considered while proportioning

* Corresponding author: rse@lntecc.com

an HSC are water to binder (w/b) ratio, paste density, particle distribution, aggregate characteristics, water contained in admixtures, air entrainment and workability.[1-3] The solid particles in an HSC range a great deal in size, which is from submicron up to millimeters. In particular, the aggregate content which accounts about 70% of HSC volume exerts significant contribution to the stiffness of concrete. However, the overall performance of HSC depends on the distribution of such aggregate.[2,4] Besides, the aggregate characteristics like shape and texture also influences the fresh (workability, finishability, bleeding, pumpability, and segregation) and hardened properties (strength, stiffness, shrinkage, creep, density, permeability) of HSC.[5,6] However, in this study, the distribution effect of coarse aggregate on the properties of an HSC mix that has been designed for a real time housing project were examined. To investigate on the fresh and hardened properties, the laboratory tests like semi-adiabatic calorimetry, slump, rheology, air content, compressive, tensile and flexural strengths, static elastic modulus, chloride ions migration and water permeability were conducted on the five HSC mixes made with different aggregate packings. With this study, our research team had developed a robust HSC mix with improved strength and durability, and such mix has been later recommended to the project site.

2. EXPERIMENTAL PROGRAM

2.1 Materials and mix design

In this study, an HSC mix designed for a real time housing project was considered. This mix was prepared using 53 grade ordinary Portland cement conforming to the Indian standard (IS) 12269[7], ground granulated blast furnace slag, potable water, polycarboxylate ether-based superplasticizer with 35% solids content and crushed stone as fine (size ≤ 4.75 mm) and coarse aggregates (sizes 10 mm and 20 mm). These aggregates were sourced from a nearby granite quarry and the same was used in the preparation of all HSC mixtures. The physical properties of cement and aggregate were tested as per IS 4031-5[8] and IS 2386-3[9] standards. The specific gravity and soundness of raw cement tested using Le-Chateliers Apparatus were 3.15 and 2 mm, respectively.

The specific gravity, water absorption and bulk density of 20 mm (2.87, 0.39%, 1.56 kg/lit), 10 mm (2.87, 0.49%, 1.58 kg/lit) and less than 4.75 mm (2.67, 1.6%, 1.65 kg/lit) sized aggregates were tested and they were found to be within the permissible limits. Table 1 show the detail of different HSC mixes prepared in this study. The major variable in the design of such HSC mixes was the change in proportions of 10 mm and 20 mm sized aggregates. As per IS 2386-1[10], the sieve analysis test was conducted on the total aggregates used in each HSC mix and the resultant gradation curve is plotted (Fig. 1).

Table 1· Mix proportioning by weight of the different HSC mixes

Mix ID	**Aggregate (%) (out of 100)**			**Powders (%) (out of 100)**		**w/b ratio**	**PCE (%)**
	20 mm	**10 mm**	**≤ 4.75 mm**	**Cement**	**Slag**		
Mix-1	0	65					
Mix-2	30	35					
Mix-3	35	30	35	50	50	0.22	0.4
Mix-4	40	25					
Mix-5	65	0					

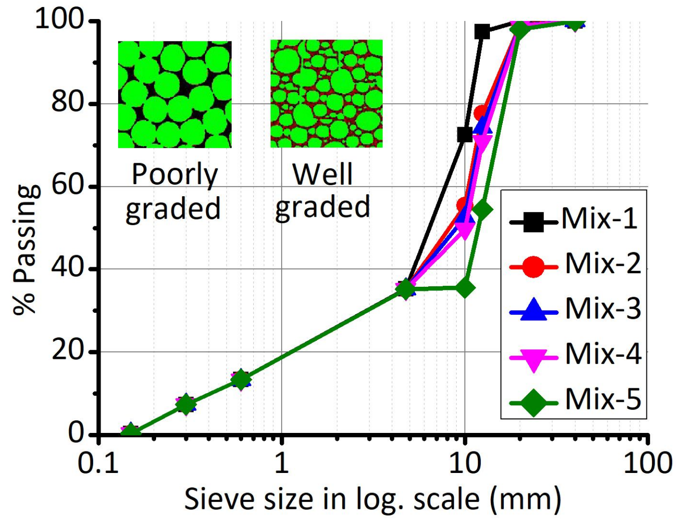


Fig. 1· Gradation curve of the aggregates used in the five HSC mixes

Other than Mix-1 and Mix-5, the remaining three mixes were found to have same gradation curve. The aggregate used in these three mixes were found to be well-graded and suitable to be used in the HSC preparation. The raw materials were batched using a weigh balance (100 g minimum accuracy). Such ingredients were mixed in a 60-liter laboratory-based concrete mixer for up to 4 mins at room conditions (25°C and 65% relative humidity). The fresh mixes were loaded into the test moulds in three layers in a timely manner and the top concrete surface was finished with care using a tapping knife. Vibration table was used to consolidate such concrete mixes. After 24 hrs, the specimens were demolded and then cured in potable water for up to 7 and 28 days.

2.2 Test procedure

2.2.1 Isothermal and semi-adiabatic field calorimeters

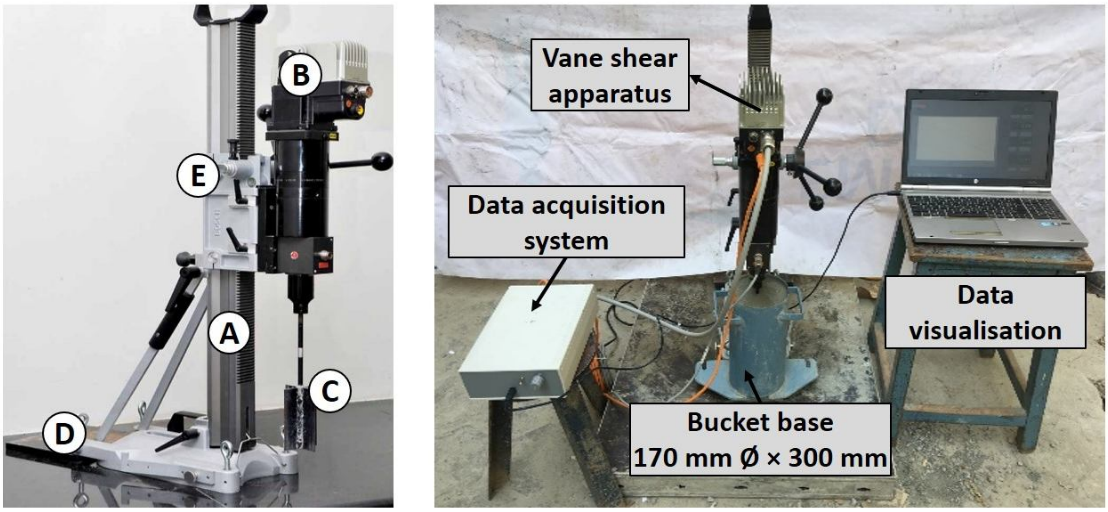
In this study, the cement was partially replaced with slag in all HSC mixes. 30 g of fresh cement pastes prepared with 0 and 50 wt% slag content was loaded in a timely manner into the I-Cal 8000 high precision calorimeter, confirming the ASTM C1702[11] standards. This test was conducted at 25°C temperature and 65% relative humidity and then run for 42 hrs. Both the paste samples were prepared with 0.22 w/b ratio. The heat liberated from the fresh HSC mixes were also studied using F-Cal 4000 semi-adiabatic field calorimeter as per ASTM C1753[12]. About 2 kg of fresh concrete sample was used to perform such test for 48 hrs at room conditions.

2.2.2 Slump spread, air content and Vane shear test

The slump test on fresh concrete was done using a standard slump cone and tamping rod (IS 1199[13]). This test was repeated three times to avoid the measurement variabilities. The air content formed in the fresh concrete was found using a type B pressure meter (ASTM C231[14]), and the average of three readings were calculated. The Vane shear test on fresh concrete was conducted as per the procedure suggested in Abd Elaty and Ghazy[15]. Fig. 2 show the Vane shear test assembly. This experiment was conducted to assess the rheological behaviour of fresh concrete. Up to 75% volume of the bucket base was filled with the concrete. Next, the Vane shaft was gradually inserted into the bucket. Once after setting the Vane in a vertical position, the torque meter could run at a constant speed (20 rotations/min). The maximum torque (T_{max}) which collapsed the interstructural bonds in the HSC mixes was noted. The yield stress (τ_y) of concrete is determined by applying such torque value in Eq. 1.

Yield stress, $\tau = 2T_{max} / \pi h D^2$ - (1)

Where h and D are the concrete filling height and diameter of the vane used in this study.



A – Supporting steel frame, B – High power torque head, C – Vane with four blades (140 mm Ø × 120 mm), D – Base plate, E – Adjustable screws

Fig. 2· Vane shear test assembly

2.2.3 Mechanical tests

Prismatic (of size 150 × 150 × 750 mm), cylindrical (150 Ø × 300 mm) and cubic (150 × 150 × 150 mm) shaped HSC specimens were cast to evaluate their hardened properties. As per IS 516[16], the compressive strength of cube specimens was tested after 7 and 28 days by applying a load rate of 140 $kg/cm^2/min$. This displacement-controlled test was performed using a closed loop, servo-controlled compression testing machine having 3000 kN maximum capacity (ELE International, United Kingdom). The compressive strength was determined by dividing the load at failure with the specimen cross-sectional area. The split tensile strength of HSC cylinders was tested according to IS 5816[17]. The test procedure includes the alignment of specimen in the direction of load, fixture of packing strips, and finally applying load (1.2-2.4 MPa/min) without shock. The split tensile strength (σ_t) was calculated using Eq. 2.

$$\sigma_t = 2P / \pi l d \qquad - (2)$$

Where ‘P’ is the maximum load at failure, ‘l’ and ‘d’ are the length and diameter of specimen. As per ASTM C469[18], the static elastic modulus of HSC cylinders was determined using a 1200 kN capacity system (MTS Systems Corporation, United States). Prior to this testing, the cylinder ends were sulfur capped and ground in order to achieve a flat contact surface. Three EPSILON compressometers (0.02 µm accuracy and ± 1.5 mm travel distance) were fixed on to the specimens to record the strains. These three strain gauges were placed equidistant around the specimen circumference over a 150 mm gauge length. The lock knob in such gauges were then released to allow their free movement during the experiment. The load ramp was applied in three cycles (loading rate 4.42 kN/sec), between 5-40% of expected ultimate compressive load. The stress-strain curve was recorded using a data acquisition system and then plotted. The slope of the loading region in third cycle gives the elastic modulus. The flexural strength (σ_f) of prismatic specimens was found by performing the test as per the central point load method suggested in IS 516[16] using 150 kN capacity MATEST flexural testing machine (Italy). First, the specimen and load carrying blocks were aligned and then load applied at a rate of 400 kg/min to find the flexural strength (Eq. 3). The average of three readings were calculated.

$$\sigma_f = Pl / bd^2 \qquad - (3)$$

where ‘P’ is the maximum load at failure, ‘l’, ‘b’ and ‘d’ are the specimen length, breadth and depth.

2.2.4 Durability tests

Cubic (150 × 150 × 150 mm) and cylindrical (100 Ø × 200 mm) specimens were cast to perform the water permeability and non-steady state chloride migration co-efficient test as per German Standard DIN 1048[19] and NT BUILD 492[20] (Australian code of practice). The 28-day cured cylindrical specimens were sliced into four halves using a diamond-tipped precision saw and the inner cut-sections were used to examine the depth of chloride (Cl^-) ions penetrated. As per DIN 1048[19], the dried cubic specimen was exposed to a constant water pressure of 0.5 MPa for 3 days. The pressure is then applied perpendicular to the mould filling direction, either from above or below the specimen. The water pressure was released after 3 days and the tested specimen was next cut into two halves to measure the maximum depth of water penetrated.

The chloride migration test principle is same as rapid chloride permeability test, involving the application of a 30 V potential gradient across the vacuum saturated concrete slice, where one side was in contact with 0.3 M sodium hydroxide solution and the remaining was exposed to 10% sodium chloride solution. The potential was applied for 24 hrs and the tested specimen was split into two halves. The inner split surfaces were sprayed with the silver nitrate solution to inspect the Cl^- ions reactivity with the cement matrix. When the Cl^- ions react with $AgNO_3$ solution, the surface turns white in colour. The extent of white-coloured regions across the split surface were inspected, which gives the depth of Cl^- ions penetrated. With this value, the non-steady state migration co-efficient was calculated using the Eq. 4.

$$D_{nssm} = (RT / zF((U-2)/L))\cdot(((X_d - \alpha(X_d))/t) \qquad - (4)$$

Where D_{nssm} is Non-steady-state migration coefficient (m^2/s), z is absolute value of ion valence (z=1 for Cl^- ions), F is Faraday constant (9.648×10^4 J/(V·mol)), R is gas constant (8.314 J/(K·mol)), T is temperature, U is absolute value of applied voltage (V), L is specimen thickness (m), X_d is measured depth of chloride penetration (m), α is co-efficient and t is test duration (secs).

3. RESULTS AND DISCUSSION

3.1 Gradation of aggregates

The aggregates used in the concrete making process is of various sizes, and their distribution is termed as gradation.[21] The aim of aggregate proportioning and sizing is to achieve a maximum volume of aggregate in the concrete without affecting the balance in between strength, workability and finishing.[3] This study proposed five different aggregate packing by varying the proportion of 20 mm and 10 mm sized coarse aggregates (Table 1). The content of fine aggregate in such packings was maintained the same. The well-graded aggregates produce a densely packed workable concrete.[22,23] The well-graded and gap-graded aggregates are characterised by a S-shape and a hump in their gradation curves (Fig. 1). The aggregate packing designed for Mix-1 and Mix-5 was gap-graded, whereas the remaining mixes have well-graded aggregates in them. Zhao *et al.*[22] have reported that the concrete proportioned with well-graded aggregates consumed lesser volume of cement paste than the concrete packed with single-sized aggregates. Besides, the concrete with well-graded aggregates showed lesser shrinkage, strong and durable than the other case. The concrete packed with gap-graded aggregates is vulnerable to segregation in plastic state under vibration.[3]

3.2 Heat of hydration

Fig. 3 show the 42-hr calorimetry result of the 0 and 50 wt% slag-based cement pastes. It was noticed from the heat flow curve that these cement mixes showed exothermic reaction when the water was added into them. The partial replacement of cement with slag had significantly affected the early age cement hydration. However, the slag presence could assist in pozzolanic reaction at late ages.[1,3] The IS 456[24] recommended the slag use up to 75 wt% in the HSC preparation. In this study, the cement content in HSC mixes was replaced with 50 wt% slag, which is well below the IS 456[24] limits. Other than the cement pastes, the heat of hydration liberated from the five HSC mixes were tested using semi-adiabatic calorimetry.

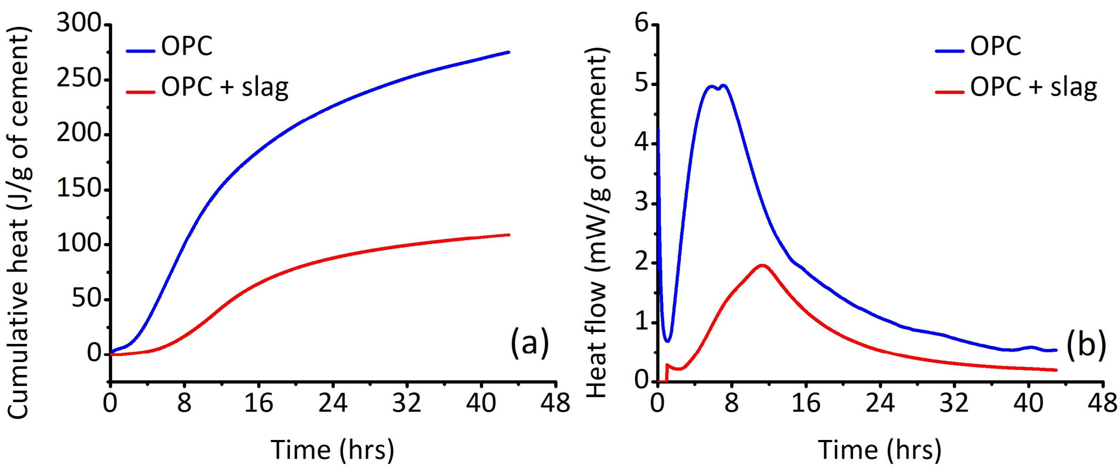


Fig. 3· Isothermal calorimetry results (a) cumulative heat vs. time and (b) heat flow vs. time of the 0 and 50 wt% slag-based cement pastes

Fig. 4 show the temperature change in the concrete samples measured during the hydration in a calorimeter. The different initial temperatures of the five HSC mixtures had not affected the total amount of the hydration heat emission rate. The temperature of Mix-1, Mix-2, Mix-3, Mix-4 and Mix-5 had reached a maximum of 32.7°C, 31.5°C, 33.7°C, 31.8°C and 31.6°C within 22 hrs of casting, followed by a gradual temperature decrease which continued for the entire recorded time of 48 hrs. It seems that the cement hydration in Mix-3 was better than the remaining mixes. Other than ensuring a workable concrete, the well-graded aggregate reduces the formation of plastic shrinkage cracks, bleeding, segregation and loss of entrained air.[2] With time, the fresh cement matrix in concrete tends to shrink which is because of the progressive loss of moisture either by evaporation under direct sunlight or through hydration of cement. The aggregate presence mainly contributes to the overall stiffness of concrete, which suggests that the volume and gradation of aggregate dictates the shrinkage behaviour of concrete.[21,25]

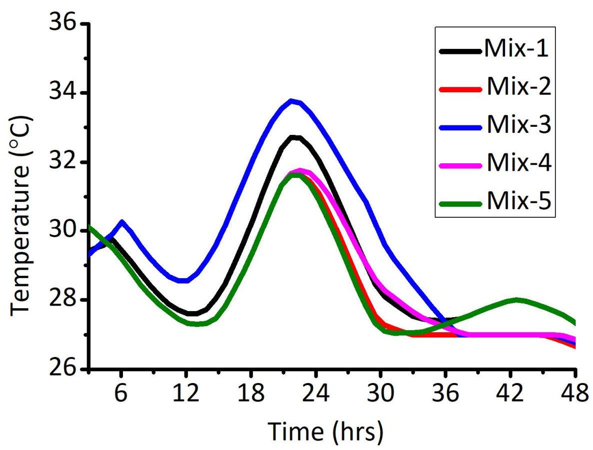


Fig. 4· Semi-adiabatic calorimetry result of the fresh HSC mixes prepared in this study

3.3 Rheology, slump, and air content

The Vane shear test gives the torque profile with operating time, see Fig. 5. In this study, the Vane was slowly turned by maintaining a constant strain rate. When the applied torque reached the maximum value, the sheared material yields and causes the concrete shearing in the area around the Vane. Due to this reason, the torque value decreased with an increase in time (Fig. 5). Ferraris *et al.*[26] have descried the yield stress of fresh concrete as a function of the volumetric fraction of solid material and the maximum packing density of the individual ingredients. The rheological behaviour of fresh HSC mixes correlate well with the Bingham's model (Eq. 5).

$$\tau = \tau_y + \mu \cdot \gamma \qquad - (5)$$

where τ, τ_y, μ and γ are the shear stress, yield stress, plastic viscosity and shear rate. Table 2 shows the yield stress, slump spread, and air content of the different HSC mixes. The shear resistance of Mix-3 was found to be lesser than the other mixes, which shows that the proper gradation gives the most flowable suspensions and highest packing density in concrete.

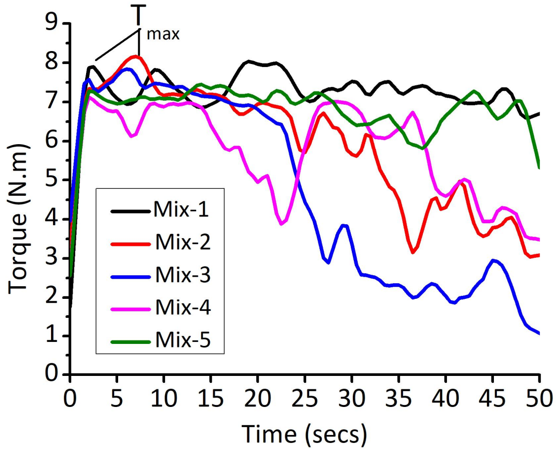


Fig. 5· Change in torque value with time obtained during the Vane shear test

Table 2· Yield stress, slump, and air content of the different HSC mixes

Properties (20/10 mm agg. wt%)	**Mix-1 (0/65)**	**Mix-2 (30/35)**	**Mix-3 (35/30)**	**Mix-4 (40/25)**	**Mix-5 (65/0)**
Yield stress (kPa)	7.98±0.22	8.48±0.34	7.39±0.55	8.92±0.11	8.82±0.13
Slump (mm)	320±12	300±21	330±11	260±17	280±10
Air content (%vol.)	1.62±0.11	1.73±0.17	1.53±0.09	1.94±0.16	2.15±0.13

Out of the five HSC mixes, the Mix-3 showed a high slump value and low air content, and this indicates that the concrete packed with equal amounts of 20 mm and 10 mm sized aggregates was workable and less porous. Such finding correlates well with the calorimetry and rheology studies. The formation of entrapped air voids (size may be 1-3 mm) is very common in low slump concrete. The major factors affecting the concrete workability are the quantities of ingredients (cement, superplasticizer, supplementary cementitious materials and water) and characteristics of aggregate (size, shape, surface area and gradation).[27] The consumption of cement and water increases when the concrete is graded with higher volume of small sized aggregates.[28] However, the Mix-4 designed with higher volume of 20 mm sized aggregate had shown low slump value, high air content and less density. This suggests that the concrete proportioned with lesser volume of small sized aggregate may cause cement loss due to bleeding and segregation. Therefore, proper gradation is required to achieve an improved workability in concrete mix.

3.4 Mechanical and durability properties

The hardened density of HSC mixes after 24 hrs of mixing time was found by subtracting the mass of concrete and mould with the mass of mould and then divided with the volume of specimen mould (of size 150 × 150 × 150 mm). The average density of HSC mixtures was found to be 2547±18 kg/m^3. The change in aggregate gradation had not affected the density of HSC mixtures but influenced their mechanical and durability properties, see Table 3.

Table 3· Mechanical and durability properties of the HSC mixes cured for 28 days

Properties (20/10 mm agg. wt%)	**Mix-1 (0/65)**	**Mix-2 (30/35)**	**Mix-3 (35/30)**	**Mix-4 (40/25)**	**Mix-5 (65/0)**
Compressive strength (MPa)	70.1±0.6	68.2±0.7	75.2±2.3	59.5±0.3	64.3±0.8
Split tensile strength (MPa)	4.93±0.12	4.84±0.23	5.07±0.31	4.42±0.11	4.64±0.17
Flexural strength (MPa)	6.7±0.3	7.5±0.4	7.2±0.4	5.8±0.6	6.4±0.2
Elastic modulus (GPa)	43.7±0.2	43.5±3.2	44.8±0.2	43.7±0.2	41.7±3.5
Water penetration depth (mm)	8±0.7	10±2.1	7±0.9	15±1.8	12±1.7
Cl^- migration (× 10^{-12} m^2/sec)	3.1±0.1	3.2±0.2	3±0.1	3.4±0.1	3.2±0.3

The average 7-day cube strength of Mix-1, Mix-2, Mix-3, Mix-4 and Mix-5 after were found as 52.5, 51.1, 56.7, 43.2 and 47.9 MPa. By maintaining a low w/b ratio, all these five HSC mixes had reached a minimum cube strength of 43 MPa within 7 days. It suggests that these HSC mixes attaining high early strength gain could be recommended in the fabrication of precast reinforced concrete elements. The cement replacement with slag could turn the concrete stronger and durable at later ages. It was found that the compressive, split tensile and flexural strengths, and static elastic modulus of Mix-3 was found to be higher than the remaining mixes. The Mix-3 was highly cohesive because of its aggregate packing, which thus resulted in better compaction, lesser formation of air voids and improved mechanical performance. Out of the five HSC mixes, the Mix-4 was found to have lesser compressive, tensile and flexural strengths. The Mix-4 was found to have a low slump and high air voids content, which was the reason behind its poor mechanical performance.

The concrete at meso scale level is considered as two-phase material comprising of matrix (including binder, pores and voids) and granular aggregates.[27] The HSC is characterised by a dense interfacial transition zone (ITZ) and acts differently from the low strength concrete. The aggregates are bonded to the matrix via the ITZ, which has low stiffness and strength than the bulk matrix. The tensile strength depends on the bond of the matrix to the aggregate grains. A larger amount of high strength cement matrix and with properly graded aggregates of high strength led to an improved tensile strength in concrete.[3] The aggregate characteristics like size, type and distribution can also influence the tensile strength of HSC.[2]

Ferraris *et al.*[26] reported that the ITZ was very weak when the aggregate was poorly graded in the concrete mix. The other factors which can affect the compressive and tensile strengths of reinforced concrete are spacing of reinforcement and thickness of concrete elements.[6] The slag addition could reduce the diffusion of Cl^- ions from the aqueous media. It was found that the Mix-3 had shown lesser water permeation depth and chloride migration co-efficient when compared to other mixes. This suggests that the proper gradation improved the cement hydration and reduced the porosity, which therefore resulted in a better durability performance. When the HSC was proportioned with nearly same amounts of 20 mm and 10 mm sized coarse aggregates, the concrete mixture was found to be workable, strong and durable.

4. CONCLUSIONS

This study examined the aggregate grading effects on the concrete properties like slump, air content, shear resistance, compressive, flexural, and tensile strengths, static elastic modulus, water permeation and chloride ions migration depths. Out of the five HSC mixes prepared with different aggregate packings, the one proportioned with same amounts of 20 mm and 10 mm sized coarse aggregate showed a better mechanical and durability performance. Such concrete with well-graded aggregates was workable and had lesser formation of entrapped air voids in them. Other than these, the proper gradation in concrete improved the cement hydration, which is evident from the calorimetry results. The concrete proportioned with single-sized aggregate showed a poor performance among the five mixes, explaining that the aggregate grading needs to be accounted as a major factor while designing an HSC mixture.

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