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EFFECT OF COARSE TO FINE AGGREGATE RATIO ON THE PROPERTIES OF THE HIGH PERFORMANCE SPECIFIED DENSITY CONCRETE.

Ali E. Abdel-Hafez, Amgad A. Hussein, Stephen E. Bruneau
Memorial University of Newfoundland, Canada
aeabdelhafez@mun.ca

Abstract: High performance specified density concrete (HPSDC) is a special type of concrete that is usually used for offshore structural applications. It is developed by partial replacement of coarse aggregate with lightweight aggregate at a specific percentage. The current study is intended to provide an enhancement to the abrasion resistance and the mechanical properties of the HPSDC through optimizing its coarse to fine aggregate ratio by volume (C/F). This is a pilot study of an ice wearing program at memorial university of Newfoundland. Six mixtures were developed with different C/F ranging from 1 to 2. The mixtures were tested according to four different ASTM standard tests. The tests were abrasion resistance, compressive strength, flexural strength (FS), and dynamic modulus of elasticity (DME). The tests results revealed that it is recommended to develop HPSDC with a C/F aggregate ratio of 1.6 as the abrasion resistance and the mechanical properties of the HPSDC showed ultimate performance at this ratio.

1. INTRODUCTION

The moving ice sheets interact with the offshore concrete structures and cause considerable wear which leads to decreased structural resistance, higher maintenance cost, and decreased operational lifetime. A good example of this would be the 1.3 billion-dollar (CAN) Confederation Bridge in Canada that links Prince Edward Island with mainland at New Brunswick. Monitoring of the bridge showed deterioration of its concrete pillars mainly around the interface between the water/ice. Some remediation and restoration work has already been proposed and is currently being carried out. Which means that abrasion resistance of a concrete to be used in offshore is an important concern. Thus, In order to develop a concrete mixture that would be suitable for offshore structures, specific consideration should be met. This fact brings a contrast, as abrasion resistance depends significantly on the aggregate type while lightweight aggregates usually do not possess high abrasion resistance. On the other hand, lightweight aggregate presence in offshore concrete mixture considered decisive to reduce the total weight of the structure and for floating considerations (Fernandes, Bittencourt and Helene 2008). That brought the need for the HPSDC which possesses lighter weight and good abrasion resistance.

HPSDC, sometimes called modified normal density concrete, is a high durability concrete developed by partial replacement of coarse aggregate by lightweight coarse aggregate at a specific percentage. HPSDC is used for offshore structural applications owing to its higher strength/weight ratio and low unit mass. This low unit mass is important to achieve the buoyancy required for offshore platforms during its towing phase. In 1991, 450,000 tons of concrete, mostly of HPSDC with 50% partial replacement of coarse aggregate by lightweight aggregate, were used in the construction of the large gravity based structure, the Hibernia platform (Hoff and Elimov 1995). In addition, it was also used in the construction of the Troll A GBS platform (Sandvik, Hovda and Smeplass 1994), which was the world largest structure ever moved at that time. The use of HPSDC enabled such a huge structure to be towed in the sea in 1996. Moreover, HPSDC is currently being used in the construction of the new gravity based structure of West White Rose. That indicates the high importance of the HPSDC and the huge cost incorporated in it. In addition, the arctic as the holder of 13% of the world's undiscovered oil and 30% of undiscovered gas (Gautier, et al. 2009), is considered as a valuable resource in the future of oil and gas. However, due to the harsh environmental condition that the concrete is subjected to at there, the exploration is still limited. That is consider and incetive for a more developed HPSDC.

Despite the huge cost and importance of such concrete, very limited researches were found in it. Bogas and Gomes (Bogas and Gomes 2014) studied the specified density concrete made with different cement content, different initial wetting conditions, different types and volumes of coarse lightweight aggregate, and effect of nanosilica addition. Then, tested its modules of elasticity.

Our study mainly focused to provide a development to HPSDC, by optimizing its coarse to fine aggregate ratio. Optimization of HPSDC C/F ratio is a two dimensional aspect as it contains changing two variables at the same time which are the lightweight aggregate content, and fine aggregate content. The study could lead to an offshore concrete with developed abrasion resistance and enhanced mechanical properties. Which in turn could lead to a far cost effective offshore structure, huge maintenance cost savings, and providing an incentive to extended construction for new offshore structures at harsher environmental regions which is highly demanded.

2. EXPERIMENTAL PROGRAM

2.1. MATERIAL PROPERTIES

General use Portland cement (GU) (ASTM C150 Type I) (ASTM C150 / C150M-18, Standard specification for portland cement 2018) was used as a binder for the developed mixtures. The lightweight aggregate that was used is STALITE expanded slate lightweight aggregate (ESLWA). It has a 12.5 mm maximum aggregate size, specific gravity of 1.53 at saturated surface dry state (SSD). It has high absorption, due to its porous nature, ranging from 6% to 9%. Table 1 shows the ESLWA physical characteristics. On the other hand, the normal weight aggregates (NWA) used, for both coarse and fine aggregate, were crushed granite stone with a specific gravity of 2.6. The normal weight coarse aggregate used has 0.6% absorption and 10 mm maximum aggregate size. The fine aggregate used has 1% absorption. ESLWA and coarse normal weight aggregates are shown in Fig. 1. Gradation analysis for all aggregates used is presented in Fig. 2. Polycarboxylate-based superplasticizer (SP) (ASTM C494 Type A and F, and ASTM C1017 Type I) (ASTM C494 / C494M-17, Standard specification for chemical admixtures for concrete 2017), (ASTM C1017 / C1017M-13e1, Standard specification for chemical admixtures for use in producing flowing concrete 2013) was used to achieve the required workability of the developed mixtures. An air-entraining agent (AEA) (ASTM C260) (ASTM C260 / C260M-10a(2016), Standard specification for air-entraining admixtures for concrete 2016) was used to improve the durability of the hardened concrete.

Table 1: Physical characteristics of ESLWA.

Absorption Saturated Surface Dry (ASTM C 127)	6.0%
Soundness (% Loss) Magnesium Sulfate (ASTM C 88) (ASTM C88-13, Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate 2013)	0 - 0.01%
Sodium Sulfate (ASTM C 88) (ASTM C88-13, Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate 2013)	0 - 0.23%
25 Cycles Freezing and Thawing (AASHTO T 103)	0.22 - 0.80%
Toughness Los Angeles Abrasion (AASHTO T 96)	25 - 28%
Stability Angle of Internal Friction (Loose)	40° - 42°

Angle of Internal Friction (Compacted)	43° - 46°

(a) ESLWA (b) Coarse NWA

Fig. 1. Used coarse aggregate

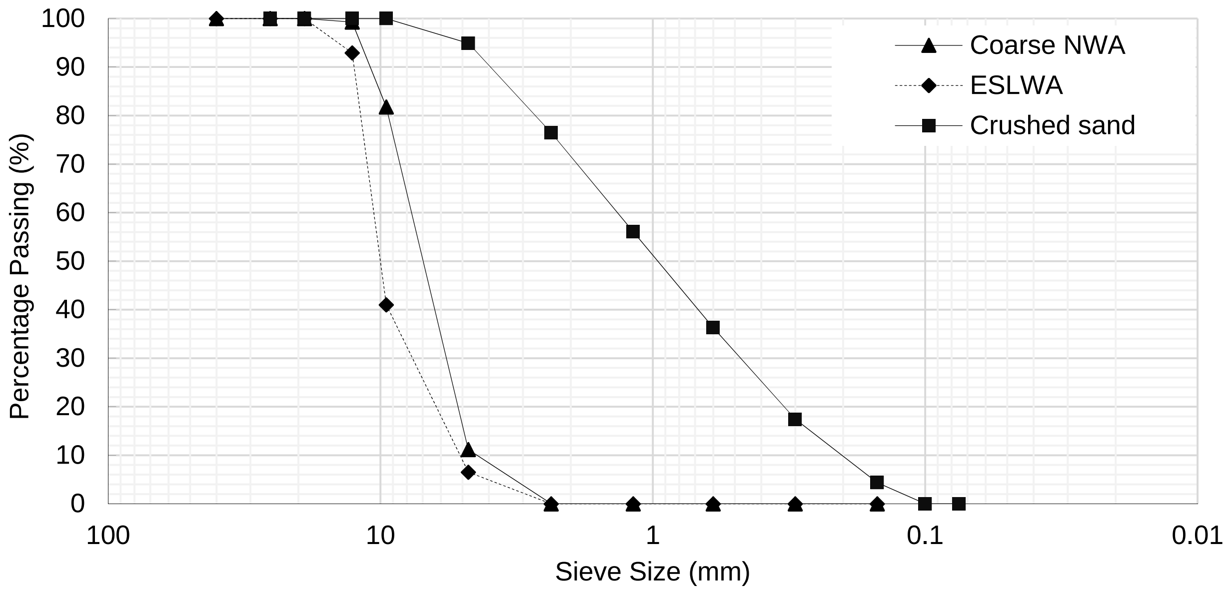


Fig. 2. Grading curves for the normal weight coarse aggregate, ESLWA, and crushed sand.

2.2. Concrete Mixtures Development

The small reinforcing bars' space of the offshore structures' elements usually requires enhanced workability (Fernandes, Bittencourt and Helene 2008). For that reason, a slump of 180 mm to 220 mm was targeted for the developed mixtures. Offshore structures are subjected to severe exposure conditions. Thus, air content of 6 - 7.5 % was targeted as recommended by ACI 318 (American Concrete Institute 2014). Trial mixtures were conducted in order to optimize the dosage of the SP to achieve the required slump without the risk of segregation. Also the dosage of AEA was carefully optimized to achieve the required air content. From each batch, 6 cylinders 100 mm × 200 mm, 6 prisms 100 × 100 mm × 400 mm, were poured. Table 3 presents the composition of the concrete mixtures.

Table 1: Composition of the concrete mixtures.

Mixture	ESLWA	N. W. A.	F. A.	C/F	SP	Density

No.	(kg/m^3)	(kg/m^3)	(kg/m^3)		(ml/m^3)	(kg/m^3)
1	228	387	774	1	2450	2104
2	248	422	703	1.2	2500	2088
3	265	451	645	1.4	2550	2076
4	280	476	595	1.6	2650	2066
5	293	497	553	1.8	2700	2058
6	303	516	516	2	2730	2050

*Note: All mixtures have 550 kg/m^3 cement content; N. W. A. = Normal Weight Aggregate; F. A. = Fine Aggregates.

2.3. Procedures

Due to its high absorption ranging from 6 to 9%, the ESLWA was kept in a soaked condition for 24 hours and then drained for a period of 6 to 12 hours prior to batching. This is a standard practice in order to achieve a near SSD case and to minimize aggregate moisture content variability (Craig and Wolfe January 2012). A similar technique was followed as suggested by Hoff during the construction of the Hibernia platform [1]. Before mixing, the fine aggregate was oven dried at 110 ± 5 C^o for 24 hours to remove the moisture content. The normal weight aggregates were saturated by a specific quantity of water based on the absorption ratio for a reasonable time to reach SSD state. The aggregates and cement were added first to the mixer. The mixer was operated for 30 seconds to blend these dry components. Then, the AEA was added in half the quantity of the batch water, added to the mixer, and mixed for 2 minutes. The SP was added to the other half of the water and mixed for additional 3 minutes. A little portion of water was kept for later usage. The batch was visually assessed to have a preliminary judgment about its consistency. If the required consistency was not met, another amount of SP was added to the remaining portion of water, added to the mixture and mixed for another minute. After visually achieving the required consistency, the batch was tested for slump and air content %. The poured test samples consists of cylinders, and prisms. The samples were compacted using a mechanical vibration table and trowel-finished to obtain smooth surfaces. Twenty four hours after pouring, the prepared samples were demolded, labeled and placed in a curing room, with a temperature of 25 ± 1.5 C^o and 100% relative humidity until required for testing. All mixtures were poured in 80 L in size.

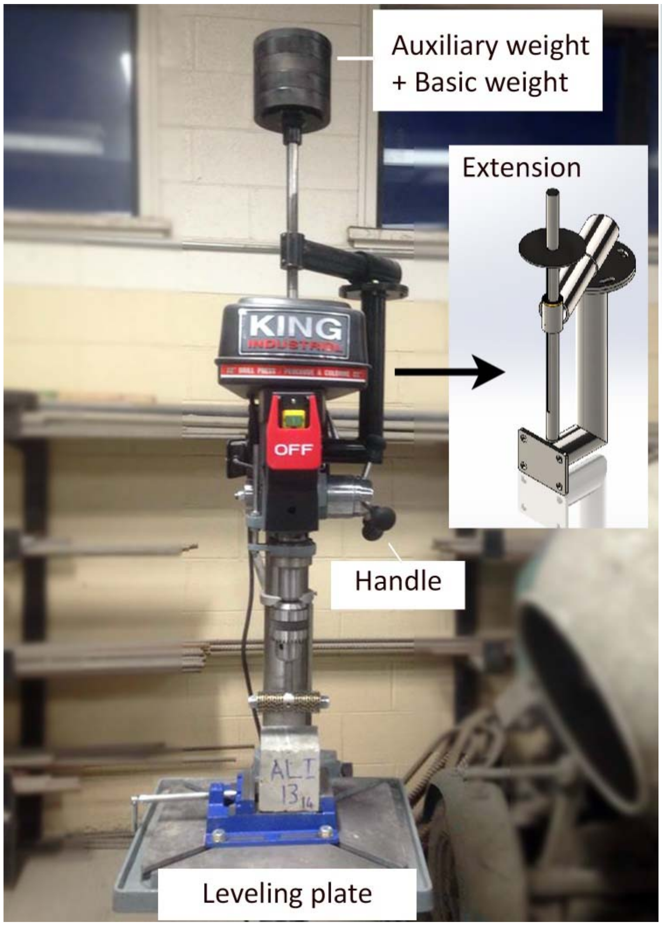
2.4. Fresh and Hardened Concrete Tests

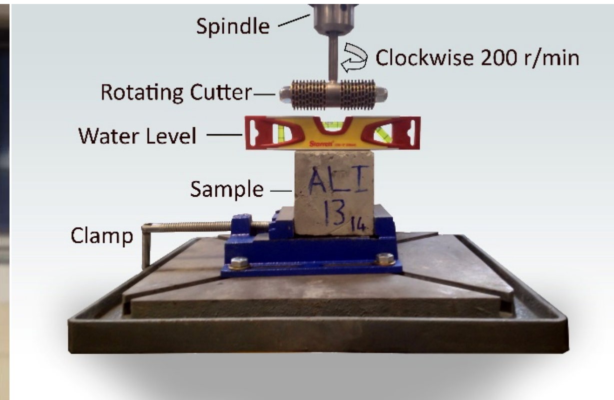
In order to evaluate the fresh concrete properties, workability of concrete mixtures and percentage of air content tests as per ASTM C143 (ASTM C143 / C143M-15a, Standard test method for slump of hydraulic-cement concrete 2015) and ASTM C231 (ASTM C231 / C231M-17a, Standard test method for air content of freshly mixed concrete by the pressure method 2017), respectively, were carried out. Hardened concrete properties were tested at 14 days and 28 days. Compressive strength according to ASTM C39 (ASTM C39 / C39M-18, Standard test method for compressive strength of cylindrical concrete specimens 2018) on three identical cylinders for each test was performed. In addition, three identical prisms were tested to evaluate the FS with third point loading according to ASTM C78 (ASTM C78 / C78M-18, Standard test method for flexural strength of concrete (using simple beam with third-point loading) 2018). Fundamental longitudinal resonance frequency of concrete prisms as per ASTM C215 (ASTM C215-14, Standard test method for fundamental transverse, longitudinal, and torsional resonant frequencies of concrete specimens 2014) was also performed to calculate the DME.

2.5. Abrasion Resistance Test

Abrasion resistance test was carried out according to ASTM C944 (ASTM C944 / C944M-12, Standard test method for abrasion resistance of concrete or mortar surfaces by the rotating-cutter method 2012) rotating cutters method. The test setup is shown in Fig. 4. It is constructed to carefully meet the ASTM C944 (ASTM C944 / C944M-12, Standard test method for abrasion resistance of concrete or mortar surfaces by the rotating-cutter method 2012) standards. The recommendations covers the loading, number of revolutions per minute (RPM), the period of testing, the cutters dimensions, and the washers and dressing wheels replacement periods. A standard drill press was modified and used as the abrasion device. The spring that was attached to the spindle was removed. A u-shape extension capable of holding the auxiliary load directly on the spindle was fabricated and installed on the drill press (see Fig.

1). The purpose of the extension was to maintain a constant load during the test time and to minimize any vibrating motion that could affect the abrasion mechanism. The test was performed at a constant speed of 200 RPM (clockwise) under a constant load of 19.7 kgs total for four minutes. This testing condition was chosen in order to produce the highest abrasion damage within the constrains set by the ASTM procedure. The rotating cutters were constructed with 22 dressing wheels and 24 washers with an overall diameter of 82.5 mm. The abrasion test was performed at 14 and 28 day on three formwork adjacent surfaces of different 100 mm × 100 mm × 100 mm cubes that were carefully cut from different prisms. After testing the samples, the surface was cleaned from remaining debris by using compressed air, then the abrasion depth was measured. .





(b) Enlargement of the rotating cutters and the sample.

(a) Drill modification.

(c) Enlargement of the rotating cutters.

Fig. 3. Abrasion resistance test setup.

3. DISCUSSION OF RESULTS

3.1. Workability of Fresh Mixtures

Coarse to fine aggregate ratio have a direct influence on the inter-particle friction. That appears by increasing the C/F aggregate ratio gradually. Mild increase in the SP dosage was required (see Table 2). In which, when comparing the HPSDC with C/F aggregate ratio of 2 with C/F aggregate ratio of 1, higher dosage by 11.4% was needed to achieve the required workability. Percentages of air contents did not vary significantly and mostly it was in the targeted range of 6 – 7.5%.

3.2. Abrasion Resistance

Table 3 and Fig. 4 show the 14- and 28-day abrasion depth and mechanical properties of HPSDC with different C/F aggregate ratio. Increasing C/F aggregate ratio in the HPSDC gradually from 1 to 1.6 led to a gradual enhancement in the abrasion resistance. In which, by comparing C/F of 1.6 with C/F of 1, the 14- and 28-day abrasion depth decreased by 14.6% and 13.5%, respectively. Further increase in the C/F aggregate ratio from 1.6 to 2 was not effective. In which, when comparing C/F of 2 with C/F of 1.6. The abrasion depth increased by 23.1% and 21.9% at the 14- and 28-day, respectively. This is attributed to that C/F aggregate ratio of 1.6 provided the perfect interlocking of the HPSDC. Also, as previously mentioned that increasing the ESLWA content can led to a poor performance. In HPSDC mixtures, increasing C/F aggregate ratio includes increasing ESLWA content. Thus, this fact may be a participator in the reduction occurred when C/F changed from 1.6 to 2.

Table 2: Abrasion depth and mechanical properties of tested mixtures

Mixture #	Mixture designation	Abrasion depth (mm)		f'_c (MPa)		FS (MPa)		DME (GPa)	
		14-days	28-days	14-days	28-days	14-days	28-days	14-days	28-days
1	1CF	0.279	0.267	61.01	63.16	6.23	6.52	34.23	34.68
2	1.2CF	0.263	0.255	64.67	67.59	6.71	7.15	36.11	36.80
3	1.4CF	0.255	0.243	66.99	71.38	7.25	7.66	37.23	38.10
4	1.6CF	0.239	0.231	71.02	73.08	7.85	8.10	38.20	39.26
5	1.8CF	0.254	0.250	68.61	71.07	7.15	7.31	37.90	37.40
6	2CF	0.274	0.261	65.75	69.06	6.32	6.42	36.48	36.75

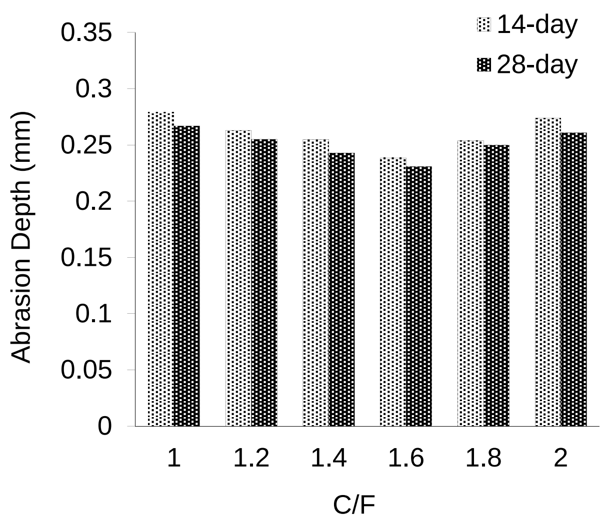


Fig. 4. Effect of different C/F aggregate ratio on the abrasion resistance of the HPSDC.

3.3. Compressive Strength

The increment in C/F aggregate ratio from 1 to 1.6 led to an upward trend in the HPSDC compressive strength as can be seen in Table 3 and Fig. 5. That increment reached its peak of 16.4% and 15.7% increments at 14- and 28-day, respectively, at C/F aggregate ratio of 1.6 compared to 1. Also, further increase in the C/F aggregate ratio in the HPSDC negatively affected the compressive strength. In which a decrement of 7.4% and 5.5% at 14- and 28-day, respectively, was noticed. Adewuyi et al. (Adewuyi, Sulaiman and Akinyele 2017) found a similar trend when changing C/F aggregate ratio within the mixture as using 45% coarse aggregate content provided the highest compressive strength, but it declined with higher C/F aggregate ratio. This behavior attributed to that, as C/F aggregate ratio increased, the thickness of the interfacial transition zone (ITZ) increased causing a reduction in the HPSDC performance, as the ITZ is a weak area with the lowest strength due to lack of cement presence.

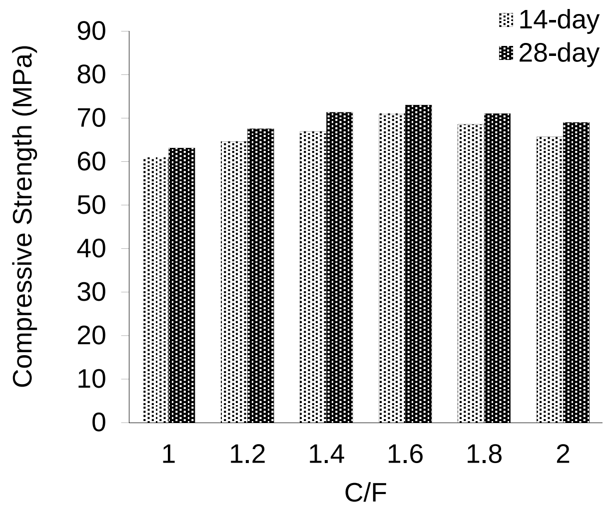


Fig. 5. Effect of different C/F aggregate ratio on the compressive strength of the HPSDC.

3.4. Flexural Strength

FS of the HPSDC was more affected as can noticed from Table 3 and Fig. 6. It increased by 26% and 24.3% at the 14- and 28-day, respectively, when the C/F aggregate ratio increased from 1 to 1.6. On the other hand, FS decreased when the C/F aggregate ratio increased from 1.6 to 2. In which, it reduced by 19.5% and 20.7% at 14- and 28-day, respectively. The morphology of the ITZ usually affect the tensile properties in a higher manner. As a result HPSDC FS was more affected by changing the C/F aggregate ratio than compressive strength.

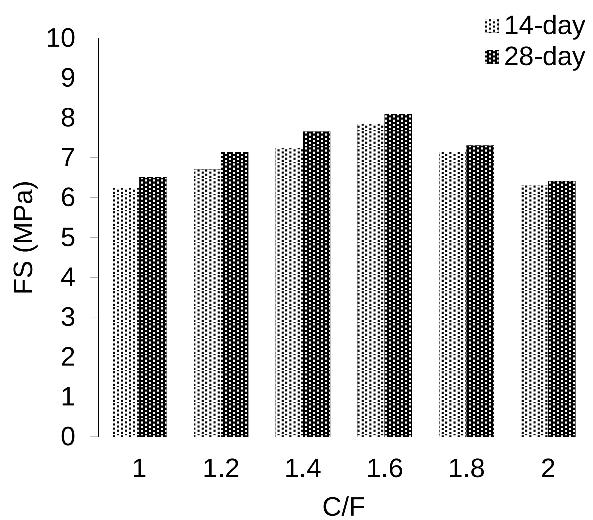


Fig. 6. Effect of different C/F aggregate ratio on the FS of the HPSDC.

3.5. Dynamic Modulus of Elasticity

As can be seen from Table 3 and Fig. 7, DME increased by 11.6% and 13.2% at the 14- and 28-day, respectively. It followed the same trend of variation as the compressive strength. In which, it reduced by 4.5% and 6.4% at 14- and 28-day, respectively. Consequently, it can be clearly seen that C/F aggregate ratio of 1.6 is the ideal proportioning for HPSDC with 50% replacement of coarse aggregate with the ESLWA.

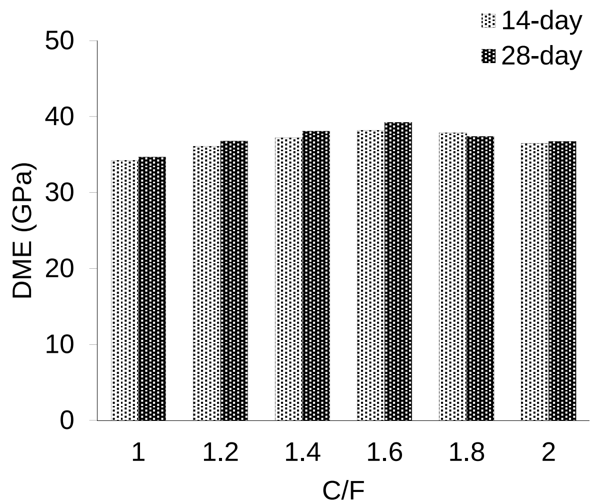


Fig. 7. Effect of different C/F aggregate ratio on the DME of the HPSDC.

4. CONCLUSIONS

From the above analysis and discussion it can be concluded that:

1. Thorough affecting the inter-particle friction, increasing C/F aggregate ratio increased the demand for SP dosage to achieve the targeted workability of the HPSDC mixtures.

2. Increasing C/F aggregate ratio to 1.6 positively impacted the abrasion resistance of the HPSDC by an average of 14%, However, higher HPSDC C/F aggregate ratios was not as effective.

3. Increasing C/F aggregate ratio to 1.6 affected the HPSDC ITZ properties which led to enhanced compressive strength by an average of 16.1% and enhanced DME by an average of 12.4%. Also higher C/F aggregate ratios was not effective.

4. Higher impact was noticed on the HPSDC FS behavior by increasing the C/F aggregate ratio from 1 to 1.6 by an average of 25.2%. Also, 1.6 C/F aggregate ratio showed the highest FS performance.

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