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Making high strength concrete using Maddhapara hard rock as coarse aggregate

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Abstract

This study has been conducted to understand the possibility of utilization of Maddhapara hard rock aggregate as coarse aggregate for making high strength concrete. For this, hard rock aggregates were collected and investigated for physical and mechanical properties. Concrete specimens of size 100 mm by 200 mm were made by varying water-to-binder ratio (W/B) (0.30, 0.35, 0.40, 0.45), cement content (450 kg/m^3 and 500 kg/m^3), type of cement (CEM Type I, CEM Type II AM and CEM Type II BM). Also, a part of the cement (8%) was replaced by silica fume (36 kg/m^3 to 40 kg/m^3). 444 cylindrical concrete specimens were made for 37 different mixture proportions of concrete. The specimens were tested for compressive strength, stress-strain curve and modulus of elasticity of concrete at 7 days, 14 days, 28 days, 56 days, and 90 days. Specimens were also tested for tensile strength of concrete at 28 days. In addition to the concrete specimens, 222 mortar cube specimen (2 inch × 2 inch × 2 inch) were also made by screening concrete of each mixture through #4 sieve. The mortar specimens were tested at 28 days and 90 days. From the experimental results, it was revealed that hard rock aggregate can be utilized as coarse aggregate for making high strength concrete from 40 MPa to 78 MPa. Relationships between compressive strength and tensile strength, compressive strength and modulus of elasticity, and stress and strain of concrete made with Maddhapara hard rock aggregate are proposed.

Keywords: Compressive strength, water-binder ratio, silica fume, Maddhapara hard rock, high strength concrete.

1. Introduction

As per the plan of the present government, Bangladesh will become a middle income country by Year 2041. To achieve this goal, government has taken initiatives to construct several mega structures like Metro Rail Project, Padma Bride Project, Paira Port Project, Dhaka Elevated Expressway Project, Matarbari Deep Sea Project, and so on. For making these structures, it is necessary to utilize high strength concrete. Due to the limited resources of high quality coarse aggregate, it is a big challenge for us for making high strength concrete. In most of the projects, aggregates are imported from several countries, like India, Malaysia, China, Qatar, etc. High strength concrete (HSC) is not a new material. The production of this material became possible after invention of chemical admixture as well as utilization of mineral admixtures in concrete. Globally, a lot of studies were conducted on the production of high strength concrete (Aitcin, 1990) (Hassan, 2000) (Memon, 2002) (Rosenberg, 1989) (Chen, 2008) (Nagataki, 2002).

These studies concluded that for making HSC the importance of mineral and chemical admixtures is very significant. In fact, it became possible for making high strength concrete with the utilization of mineral and chemical admixtures. In addition to the high strength, high strength concrete reduces chloride ingress in marine environment. It also reduces carbonation rate of concrete in atmospheric environment.

Table 1
Material properties of coarse and fine aggregates

Parameter	Types of Aggregate	
	Maddhapara Hard Rock Aggregate	Fine Aggregate
Specific Gravity (SSD)	2.75	2.60
Absorption Capacity (%)	0.58	4.0
Wear Value (%)	23.6	-
Grading	15mm – 10mm: 60% 10mm – 5mm: 40%	4.76mm – 2.38mm: 2.5% 2.38mm – 1.19mm: 12.5% Below 1.19mm: 85%
Fineness Modulus (FM)	6.60	2.64

Table 2
Mineralogical compositions of hard rock

Maddhapara Hard Rock Aggregate	Weight (%)						
	SiO_2	CaO	Fe_2O_3	Na_2O	MgO	Al_2O_3	K_2O
Maddhapara Hard Rock	62.7	20.4	8.0	6.3	5.3	6.0	0.8

Table 3
Variables considered for making specimens

Cement Type	CEM I				CEM Type II A/M				CEM Type II B/M	
Cement Content (kg/m^3)	450	414	500	460	450	414	500	460	500	460
Silica Fume (kg/m^3)	0	36	0	40	0	36	0	40	0	40
w/c	0.30, 0.35, 0.40, 0.45									
Super-plasticizer (Chemical Admixture)	Sulfonated naphthalene-formaldehyde condensate (SNF) 0.5% of the binder content.									
Sand to Aggregate Volume Ratio	0.36									

To explore the possibility of making high strength concrete using locally available aggregates, a study was conducted (Sarwar, 2012). It was found that by using locally available materials (both as coarse and fine aggregates), it is possible to produce concrete of strength 40 to 50MPa. Some studies were also conducted by other researchers for producing high strength concrete in Bangladesh (Rashid, 2009). No detailed studies were conducted to explore the possibility of utilization of Maddhapara hard rock as coarse aggregate for producing high strength concrete in Bangladesh. Therefore, this study has been planned for making high strength concrete by utilization of Maddhapara hard rock. 444 concrete samples and 222 mortar samples were made by varying W/C, cement content, abd silica fume content. The specimens were tested for mechanical properties of concrete at 7 days, 14 days, 28 days, 56 days and 90 days. The results of this experimental investigations are summarized in this report.

2. Experimental method

2.1 Materials

Stone chips from Maddhapara hard rock quary site was collected. Maximum sizes of coarse aggregate was 15 mm. For producing high strength concrete, the maximum aggregate size was reduced to 15 mm from the commonly used aggregate size of 20 mm. Physical properties of aggregates, such as specific gravity, absorption capacity, wear value and fineness modulus are summarized in Table 1. The hard rock aggregate shows higher specific gravity (2.75), lower abrasion value (23.6%), and also lower absorption capacity (0.6%) compared to the commonly used coarse aggregate in Bangladesh. From the abrasion value of the hard rock aggregate, it is found that the hard rock aggregate is harder compared to the commonly used stone aggregate. For making a dense grading, the aggregates were divided into two different sizes, such as 15mm ~ 10mm & 10mm~5mm. It was found that 60% (15 mm to 10 mm) and 40% (10 mm to 5 mm) combination produced maximum unit weight and minimum void. Therefore, this aggregate grading was used for making high strength concrete. Mineralogical compositions of the aggregate are summarized in Table 2. The physical properties of fine aggregates, such as specific gravity & fineness modulus are also summarized in Table 1.Same as coarse aggregate, the fine aggregate was divided into different sizes. Fine aggregates were mixed in different proportions and the unit weight and void in aggregate were measured. It was found that 2.5% (5 mm to 2.38 mm) – 12.5% (2.38 mm to 1.19 mm) and 85% (1.19 mm to 0.15 mm) combination give maximum unit weight and minimum void in the aggregates. Therefore, this grading of fine aggregate was used for making high strength concrete. Ordinary portland cement (CEM Type I as per BDS EN 197), and blended cements (CEM Type II A/M and CEM Type II B/M) were used. CEM I is purely clinker based cement. CEM Type II AM contains 80-94% clinker and 6-20% mineral admixtures, and CEM Type II B/M contains 65-79% clinker and 21-35% mineral admixtures. A part (8%) of the cement was also replaced by silica fume. Naphthalene based sulfonated naphthalene-formaldehyde condensates (SNF) super plasticizer was used to increase workability of concrete. The dosage of SNF was 0.5% of binder. Tap water was used for mixing concrete.

2.2 Mixture proportions

Concrete mixes were made using different W/B (0.30, 0.35, 0.40, and 0.45), total binder content (450 kg/m^3, and 500 kg/m^3) and types of cement (CEM Type I,CEM Type II A/M,CEM Type II B/M).Also, some cases were made with replacement of cement by silica fume (36 kg/m^3 and 40 kg/m^3). Sand-to-aggregate volume ratio was 0.36 for all cases. The variables are summarized in Table 3. Air content was assumed to be 2% as no air entraining admixtures was used. For low W/C, naphthalene based super plasticizer was used to improve workability. By varying the concrete mix design parameters, thirty-seven concrete mixes were designed. Mixture proportions of 37 cases are summarized in Table 4. The cases are defined based on the types of cement, cement content, silica fume content and W/B. As an example, the case "C08-TII AM 460 SF40 WB 0.30" indicates Case No. 08 made with CEM Type II AM cement (460 kg/m^3), silica fume (40 kg/m^3) and W/B =0.30.

Table 4
Mixture proportions

Case No.	W/B	Unit Contents (kg/m^3)							
		W	Binder (B)				CA	FA	Ch. A.
			TI	TII AM	TII BM	SF			
C01-TI 450 SF0 WB.30	0.30	135	450	-	-	-	1232	655	2.25
C02-TI 414 SF36 WB.30			414	-	-	36			
C03-TII AM 450 SF0 WB.30			-	450	-	-			
C04-TII AM 414 SF36 WB.30			-	414	-	36			
C05-TI 500 SF0 WB.30		150	500	-	-	-	1177	626	2.50
C06-TI 460 SF40WBC.30			460	-	-	40			
C07-TII AM 500 SF0 WB.30			-	500	-	-			
C08-TII AM 460 SF40 WB.30			-	460	-	40			
C09-TII BM 500 SF0 WB.30			-	-	500	-			
C10-TII BM 460 SF40 WB.30			-	-	460	40			
C11-TI 450 SF0 WB.35	0.35	158	450	-	-	-	1192	634	2.25
C12-TI 414 SF36 WB.35			414	-	-	36			
C13-TII AM 450 SF0 WB.35			-	450	-	-			
C14-TII AM 414 SF36 WB.35			-	414	-	36			
C15-TI 500 SF0 WB.35		175	500	-	-	-	1133	603	2.50
C16-TI 460 SF40 WB.35			460	-	-	40			
C17-TII AM 500 SF0 WB.35			-	500	-	-			
C18-TIIAM 460 SF40 WB.35			-	460	-	40			
C19-TII BM 500 SF0 WB.35			-	-	500	-			
C20-TII BM 460 SF40 WB.35			-	-	460	40			
C21-TI 450 SF0 WB.40	0.40	180	450	-	-	-	1153	613	2.25
C22-TI 414 SF36 WB.40			414	-	-	36			
C23-TII AM 450 SF0 WB.40			-	450	-	-			
C24-TII AM 414 SF36 WB.40			-	414	-	36			
C25-TI 500 SF0 WB.40		200	500	-	-	-	1089	579	2.50
C26-TI 460 SF40 WB.40			460	-	-	40			
C27-TII AM 500 SF0 WB.40			-	500	-	-			
C28-TII BM 500 SF0 WB.40			-	-	500	-			
C29-TII BM 460 SF40 WB.40			-	-	460	40			
C30-TI 450 SF0 WB.45	0.45	203	450	-	-	-	1113	592	2.25
C31-TI 414 SF36 WB.45			414	-	-	36			
C32-TII AM 450 SF0 WB.45			-	450	-	-			
C33-TI 500 SF0 WB.45		225	500	-	-	-	1045	556	2.50
C34-TI 460 SF40 WB.45			460	-	-	40			
C35-TII AM 500 SF0 WB.45			-	500	-	-			
C36-TII AM 460 SF40 WB.45			-	460	-	40			
C37-TII BM 500 SF0 WB.45			-	-	500	-			

W- Water, B – Binder, TI – Type I Cement, TII AM – CEM Type II A/M cement, TII BM – CEM Type II B/M cement, SF- Silica Fume, CA – Coarse Aggregate, FA – Fine Aggregate, Ch. A. - Chemical Admixture

2.3 Casting, curing and testing

A 200-liter capacity mixer pan was used for mixing concrete. Both coarse and fine aggregates were kept saturated surface dry (SSD) condition. Immediately after mixing concrete, workability of concrete was measured by a slump cone. Cylinder concrete specimens of diameter 100mm and height 200 mm were made. Also, 2 inch mortar cube specimens were made by screening each mixture of concrete through #4 sieve. The specimens were demolded after one day and kept under wet condition. The specimens are shown in Figure 1.

One day before testing of the specimens, the specimens were kept under water. The specimens were tested under a universal testing machine (UTM). During compression tests, two dial gauges were attached at a gauge length of 100 mm to measure strain over the specimens under the load. From the stress-strain curve of the specimens, modulus of elasticity of concrete was determined as per ASTM C 469. The modulus of elasticity is defined as the slope of the line drawn from a stress of 0 to a compressive stress of $0.45f_c^{'}$. Tensile strength of the specimens was measured by splitting test. The specimens were tested at 7 days, 14 days, 28 days, 56 days, and 90 days. The compressive strength and tensile strength was determined as per ASTM C 39 and ASTM C 469 respectively.

Fig. 1. Partial view of the cylinder and cube specimens.

3. Results and discussions

3.1 Unit weight of concrete

The unit weight of concrete made was measured from the weight of specimens before crushing for compressive strength. The results are shown in Figure 2. The average unit weight of concrete made with Maddhapara hard rock was found to be 2435 kg/m^3. The unit weight of concrete made with hard rock aggregate is about 6% higher compared to the normal concrete made with stone aggregate (2300 kg/m^3). The unit weight of concrete made with Maddhapara hard rock aggregate is increased due to the higher specific gravity of the hard rock aggregate.

3.2 Workability of concrete

Workability of fresh concrete was measured by slump cone. The slump of fresh concrete for all cases is shown in Figure 3. It is found that the cases with low W/C and also the cases made with silica fume shows less workability. With the use of silica fume, the workability is reduced due to the smaller sizes of silica fume particles compared to the normal cement particle. Similar results were also observed by other researchers (Nagataki, 2002). This study was conducted with naphthalene based super plasticizer with a moderate amount of dosage. The dosage of chemical admixture can be increased to improve workability of concrete further. As an alternative, polycarboxylate based new generation chemical admixture can be used to improve workability.

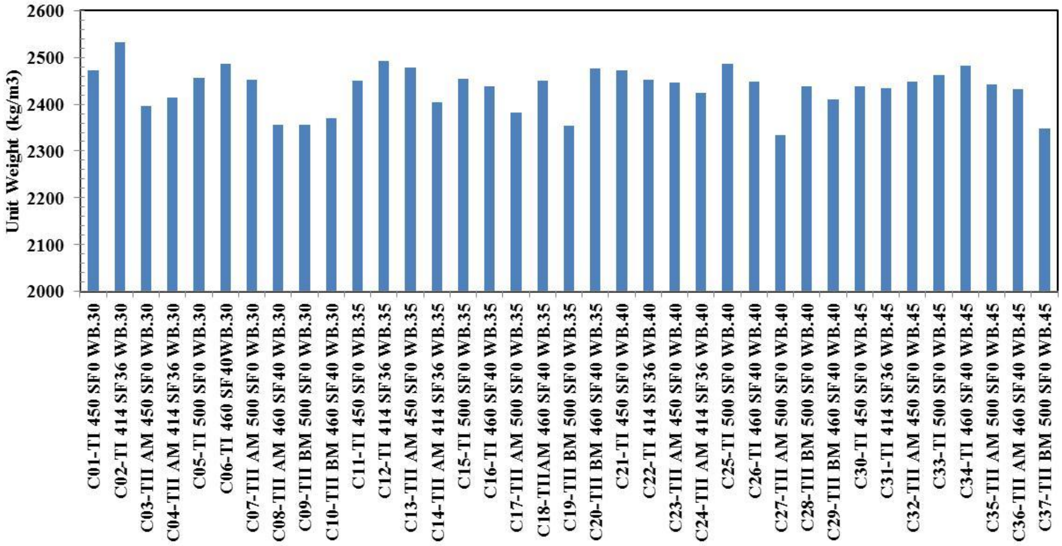

Fig. 2. Unit weight of concrete made with hard rock aggregate.

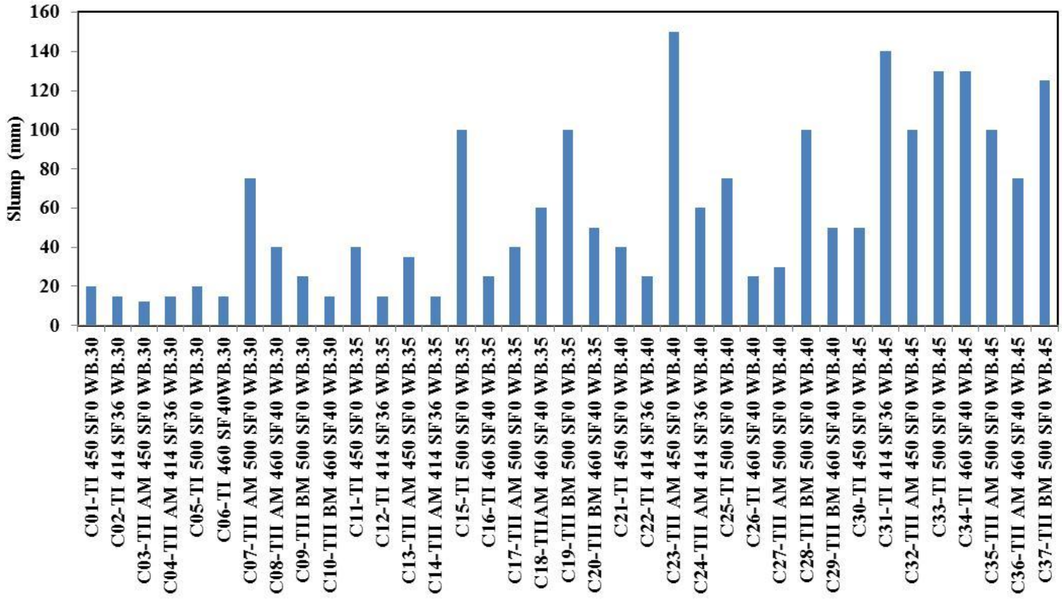

Fig. 3. Slump of fresh concrete.

3.3 Compressive strength of concrete

Compressive strengths of concrete of all cases at the ages of 7 days, 14 days, 28 days, 56 days, and 90 are shown in Figure 4, Figure 5, Figure 6, Figure 7, and Figure 8 respectively. In these figures, the cases are chronologically arranged in descending order based on the compressive strength. Irrespective of the cases, the strength of concrete is increased with time. Significant increase in strength of concrete is also observed after 28 days. The average increase in strength at 90 days compared to the 28 day's strength is found at 12% for the cases made with CEM Type I cement. However, it is raised to 15% for the cases made with CEM Type II BM cement. It is due to the slower rate of hydration of mineral admixture in CEM Type II BM cement. The effect of W/B on the compressive strength of concrete is clearly observed irrespective of the types of cement. The less is the W/B, the more is the strength.

It is clearly understood that for making high strength concrete, W/B is to be reduced based on the target strength of concrete. The effect of silica fume on compressive strength of concrete is also clearly observed. Replacing the amount of cement by silica fume increases compressive strength of concrete. Silica fume particles are purely siliceous (SiO2) and the particles are much smaller compared to the ordinary cement particle and also it has pozzolanic characteristics. These characteristics of silica fume particles improves micro-structure concrete and thereby increase compressive strength of concrete (Nagataki, 2002).

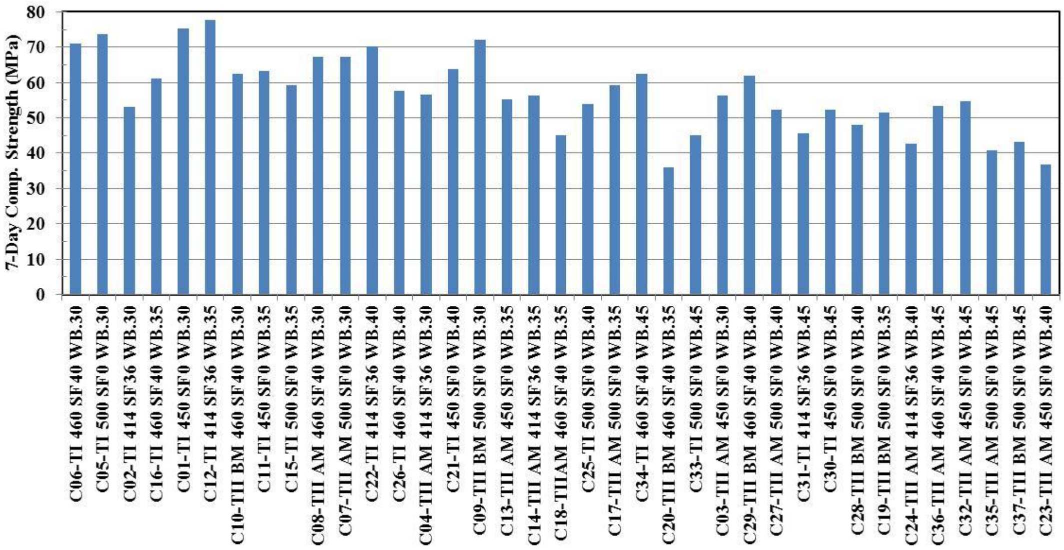

Fig. 4. Compressive strength of concrete at 7-Day.

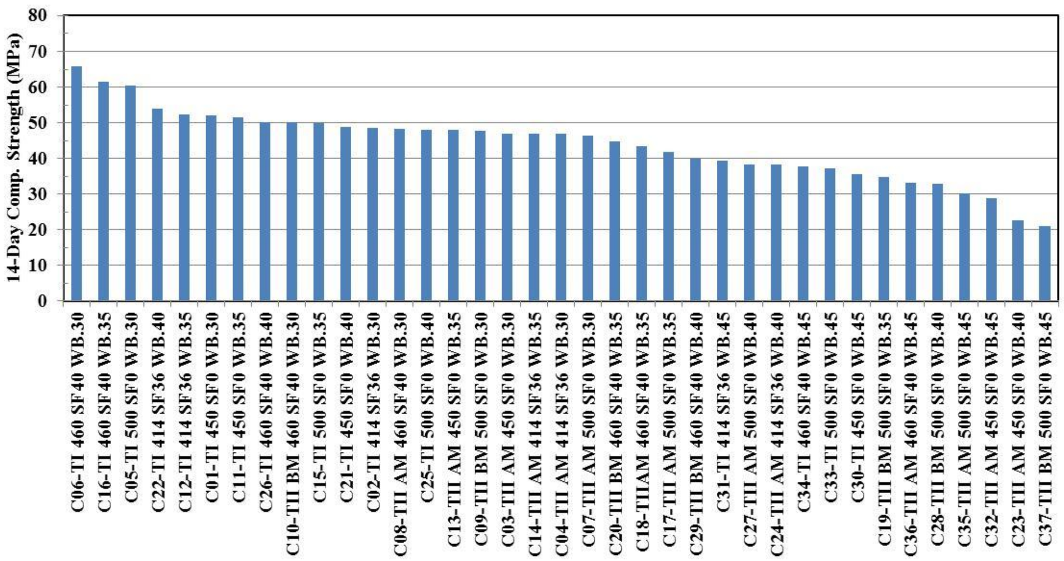

Fig. 5. Compressive strength of concrete at 14-day.

Generally, if compressive strength of concrete exceeds 40 MPa at 28 days then it is defined as high strength concrete (ACI318, 1999). It is found that out of 37 cases, compressive strength of concrete at 28 days exceeds 40 MPa for 31 cases. However, after 90 days, compressive strength of concrete exceeds 40 MPa for 33 cases. Also, it can be noted that the compressive strength of concrete exceeds 40 MPa for 19 cases at 7 days and for 25 cases at 14 days. At 28 days, the highest compressive strength of concrete of 67 MPa was observed for the case made with W/C=0.30, Cement (CEM Type I) = 460 kg/m^3, and Silica Fume = 40 kg/m^3. For this case, compressive strength of concrete is increased to 78 MPa at 90 days.

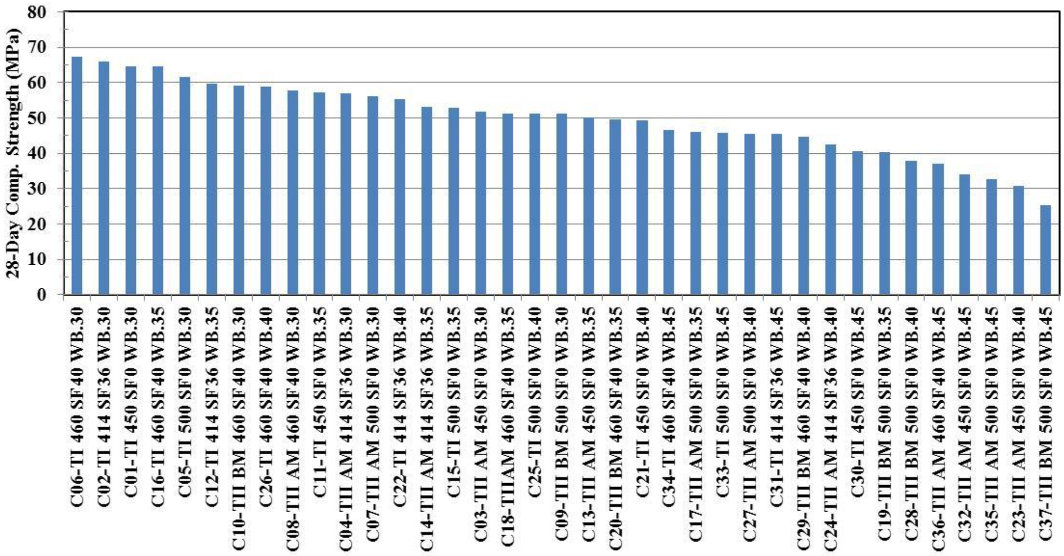

Fig. 6. Compressive strength of concrete at 28-day.

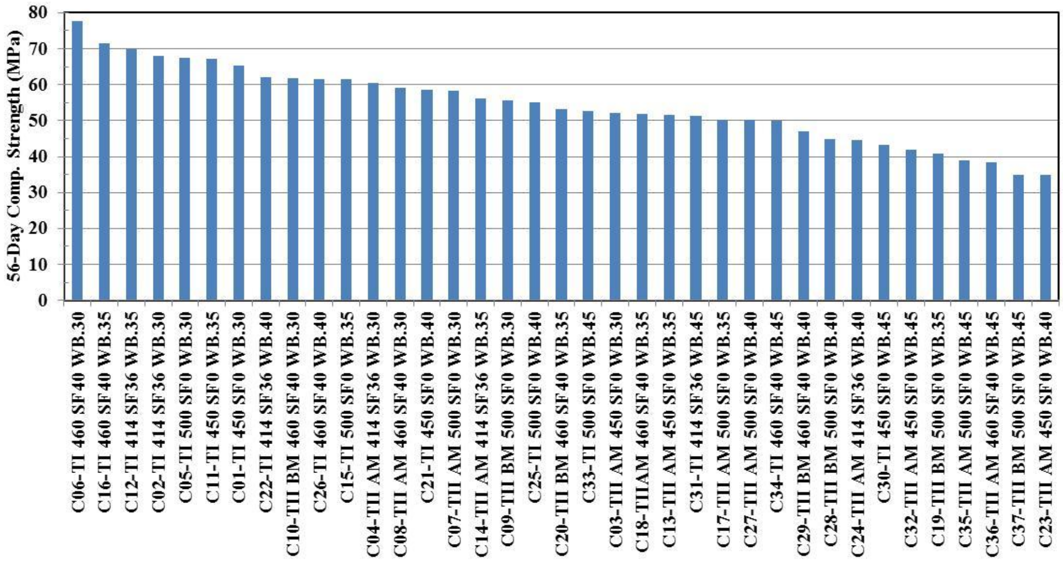

Fig. 7. Compressive strength of concrete at 56-day.

The cases with low W/B and replacement of cement by silica fume produced more compressive strength of concrete. It is also found that for making high strength concrete CEM Type IIAM and CEM Type II BM cements can also be used instead of CEM Type I cement. However, CEM Type I cement shows better performance in terms of compressive strength of concrete.

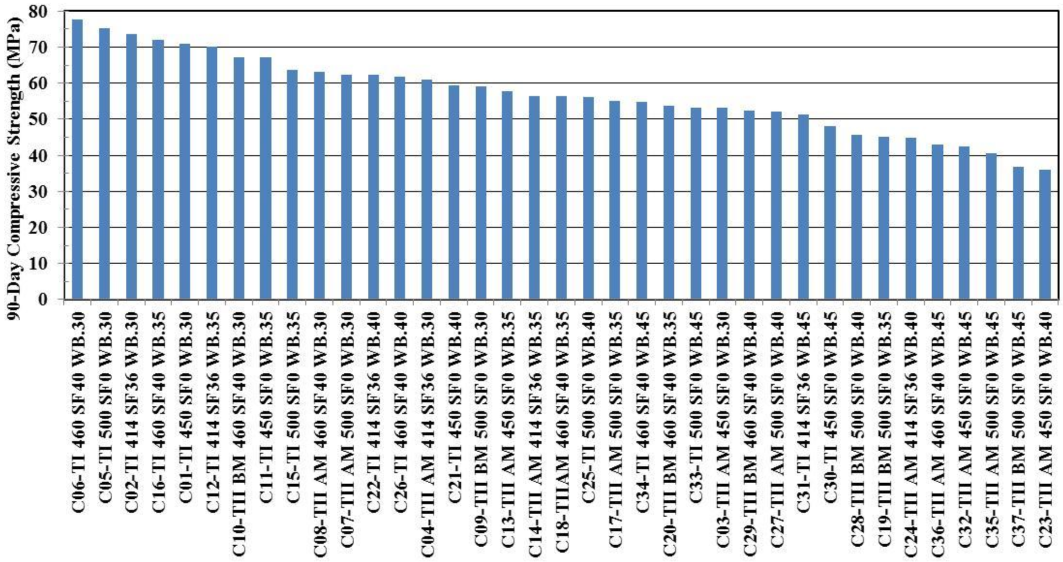

Fig. 8. Compressive strength of concrete at 90-day.

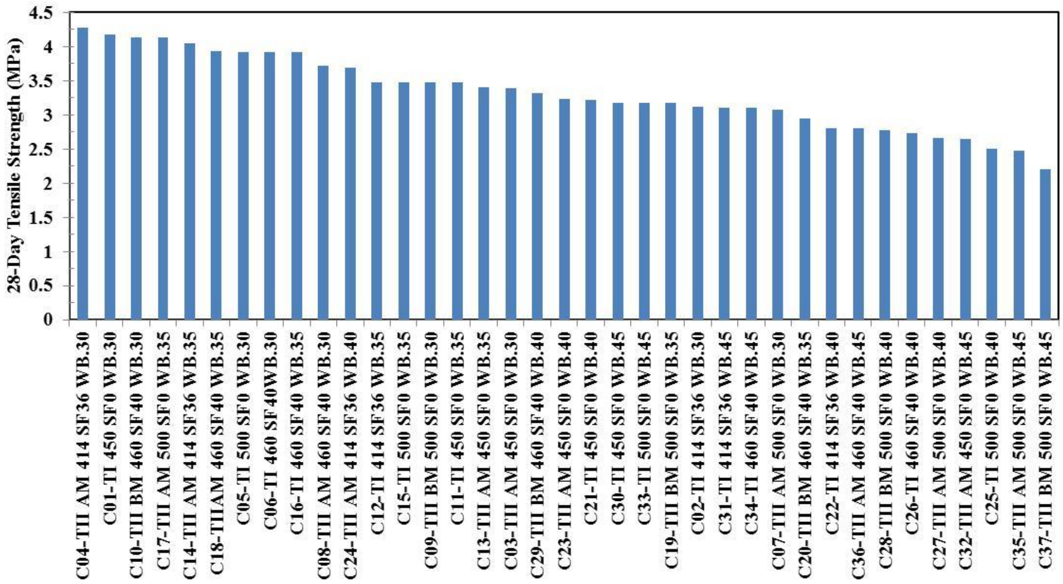

Fig. 9. Tensile strength of concrete at 28-day.

3.4 Tensile strength

Tensile strengths of concrete for all cases are shown in Figure 9. Same as compressive strength, the cases with a low W/C show more tensile strength. Addition of silica fume in concrete also increases tensile strength of concrete. The variation of tensile strength with respect to the square root of compressive strength of concrete is shown in Figure 10.

$$f_t = 0.473\sqrt{f_c'} \tag{1}$$

Where, f_t = tensile strength of concrete (MPa) and f_c' = compressive strength of concrete (MPa). The coefficient of the above-mentioned equation is 0.556 as per ACI 318 – 2014 for normal concrete aggregate specified as per ASTM C 33 (coarse and fine aggregates). It is understood that the use of equation of ACI 318-2014 will provide higher tensile strength of concrete.

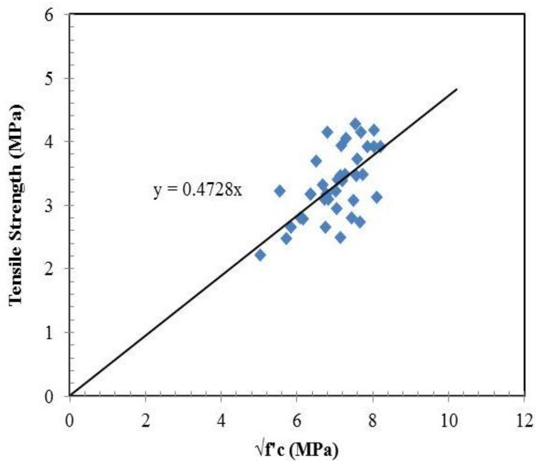

Fig. 10. Tensile strength of concrete at 28-days.

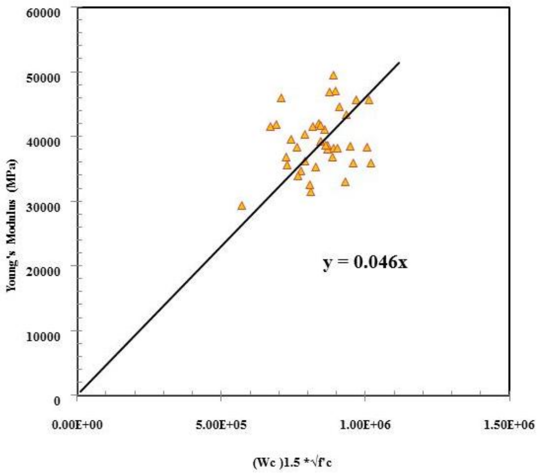

Fig. 11. Young's modulus versus $W_c^{1.5}\sqrt{f_c'}$

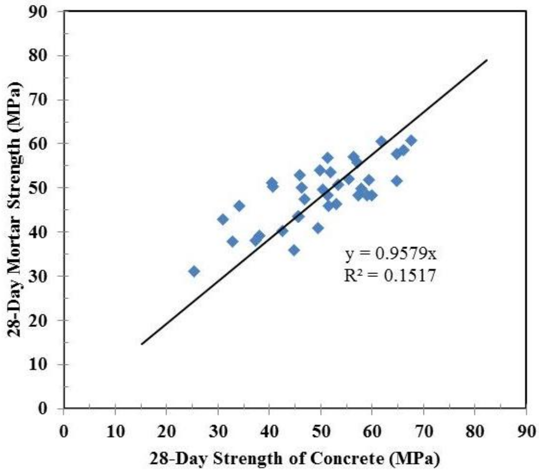

Fig. 12. Mortar strength versus concrete strength – 28 days.

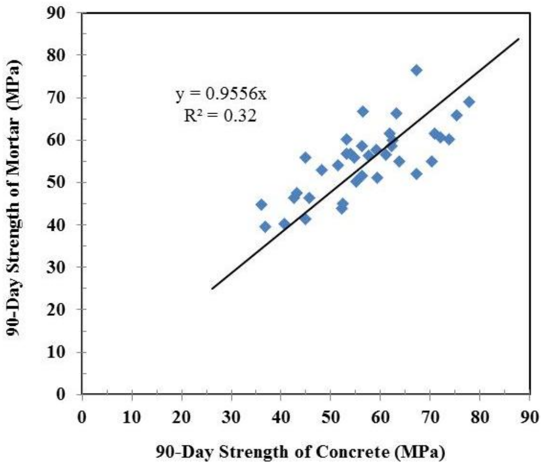

Fig. 13. Mortar strength versus concrete strength – 90 days.

3.5 Modulus of elasticity

Modulus of elasticity of concrete is sensitive to the modulus of elasticity of aggregate and mixture proportion of concrete. Therefore, an attempt has been made to correlate modulus of elasticity of concrete with compressive strength of concrete. The variation of modulus of elasticity of concrete with respect to the $W_c^{1.5}\sqrt{f_c'}$ is shown in Figure 11. The following equation is proposed for modulus of concrete made with hard rock aggregate:

$$E_c = 0.046\, W_c^{1.5}\sqrt{f_c'} \quad (2)$$

Where, E_c = modulus of elasticity of concrete (MPa), W_c = unit weight of concrete in kg/m^3, and f_c' = compressive strength of concrete (MPa). The coefficient for the above mentioned equation for the normal weight concrete is 0.0428 as per ACI 318-2014. However, a larger coefficient is found for the hard rock due to the less abrasion of aggregate (harder aggregate). Replacing unit weight of concrete as 2435 kg/m^3, the modulus of elasticity with respect to the square root of compressive strength can be correlated by the following equation:

$$E_c = 5527\sqrt{f_c'} \quad (3)$$

Where, E_c = modulus of elasticity of concrete (MPa) and f_c' = compressive strength of concrete (MPa). The above-mentioned equation can be re-written as:

$$E_c = 66556\sqrt{f_c^{'}} \tag{4}$$

Where, E_c = modulus of elasticity of concrete (psi) and $f_c^{'}$ = compressive strength of concrete (psi).

3.6 Variation of mortar strength and compressive strength of concrete

The variations of mortar strength with respect to compressive strength of concrete at 28 days and 90 days are shown in Figure 12 and Figure 13. At both 28 and 90 days, the mortar strength is found slightly lower than the compressive strength of concrete. From the fracture surface of the crushed specimens as shown in Figure 14, it was also found that the fracture surfaces crosses the specimens through the mortar part and aggregate-mortar interface. It is therefore understood that by improving strength of mortar, it will be possible to increase strength of concrete to a higher level. In this study, the maximum cement content was 500 kg/m^3. It can be raised to 550 kg/m^3. The maximum size of the aggregate was 20 mm. The size also can be reduced to 12 mm for improving the interfacial transition zone around aggregate. This study can be extended considering these parameters.

Fig. 14. Fracture surfaces of specimens.

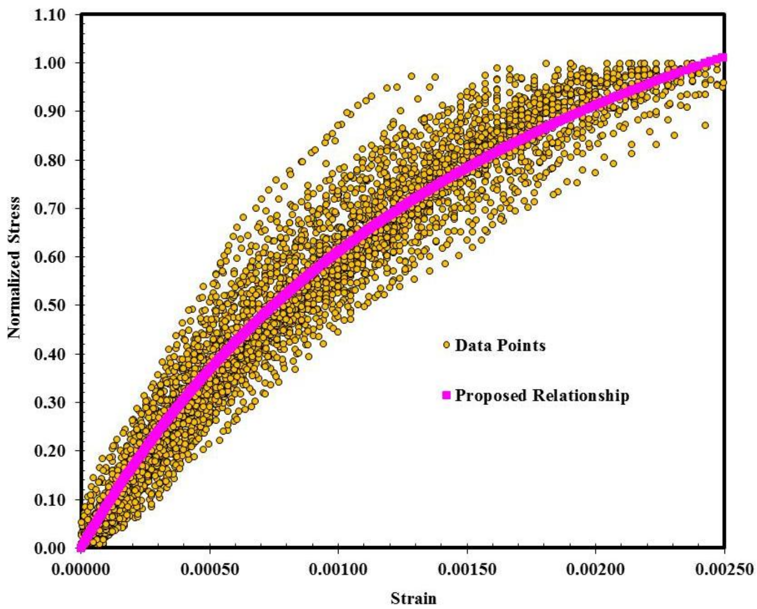

Fig. 15. Stress-strain curve of concrete.

3.7 Relationship between stress and strain

The normalized stress (normalized with respect to the compressive strength of concrete) versus strain curve is shown in Figure 15. The following non-linear stress-strain relationship is proposed for concrete made with hard rock.

$$\frac{f_c}{f_c'} = \frac{1.803\varepsilon}{0.00195+\varepsilon} \quad (5)$$

where, f_c = stress of concrete, f_c' = compressive strength of concrete, and ε = strain of concrete.

4. Conclusion

Based on the experimental investigations on utilization of Maddhapara hard rock aggregate as coarse aggregate for making high strength concrete. It is possible to use Maddhapara hard rock as coarse aggregate for making high strength concrete, out of 37 mixture proportions studied here, for 31 cases compressive strength of concrete exceeds 40 MPa at 28 days. The studied mixture proportions can be used as per the target strength requirement for high strength concrete. The case made with W/C = 0.30, CEM Type I cement = 460 kg/m^3, silica fume = 40 kg/m^3 produced maximum strength (78 MPa) at 90 days. Relationships between compressive strength and tensile strength of concrete, compressive strength and modulus of elasticity of concrete, and stress and strain of concrete are proposed.

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