Assessing Suitability of Margalla Crush for Ultra High Strength Concrete

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Abstract

A trend of high-rise buildings is emerging in Lahore. Many tall buildings having number of stories 20 to 50 (like Mubarak Centre, Pace Tower, I T Tower and Aalamgir Center etc) are under construction. Though all these structures are designed for normal strength concrete, but use of high and ultra high strength concrete shall soon become a routine. The major source of aggregate in this area is from Margalla hills near Islamabad about 300 km from Lahore. An attempt was made in the laboratory to produce ultra high strength concrete using Margalla aggregates. This effort failed rendering Margalla crush as unsuitable for high and ultra high strength concrete. However, during testing, a strange phenomenon of strength development is noted which should attract the attention of researchers for further investigation.

Key Words: Margalla crush, weak aggregates, hydration stresses, ACV, AIV, UHSC, ITZ.

1. Introduction

Use of ultra high strength concrete is still a dream in Pakistan. No doubt some laboratory experimentation has recently been conducted to achieve similar strength but its use in actual construction is not yet started. In Lahore all under-construction buildings are planned on the basis of normal to moderately high strength concretes. Increased land cost compelled engineers to plan high rise frame structures about 20 stories or more. Use of UHSC may result in major reduction in member cross-sections, hence saving a lot of precious space otherwise occupied by columns and other structural members.

Compression may induce three possible modes of failures in concrete specimen, i.e. matrix, coarse aggregate and bond failure. The key concept for making high strength concrete is to prevent these failures as far as possible [1]. A very small region between matrix and coarse aggregate is known as transition zone. Properties of both matrix and transition zone can be improved by adjusting the cement content, water to binder ratio, adding micro/pore fillers, using pozzolanas, providing sufficient rheology and reduction of void space [2] or even changing the mixing sequence. On the other hand, if aggregates do not posses required characteristics; there is no way to improve concrete properties beyond certain limits. The only option left is to use aggregate from another source. The major source of coarse aggregate used in Upper Punjab is from Margalla hills. Keeping in view the future requirements, the present study is planned to asses the suitability of Margalla crush for production of UHSC.

2. Literature Review

Concrete classifications are based on its properties in fresh as well as in hardened states. Based on 28 days strength, concrete is broadly divided into three categories i.e. NSC (normal strength concrete), HSC (high strength concrete) and UHSC (ultra high strength concrete). No specified boundaries are available to differentiate between these categories. The definition of high/ultra high strength concrete is kept on changing. In early 1940, 4250 psi (30 MPa) was considered as high strength. This level jumped to 7250 psi (50 MPa) in early 1960s. Concrete strength of 14,500-18,750 psi (100-130 MPa) is now viewed as the criteria for HSC [1]. Concrete association of Finland prescribes HSC as 10,000-14,500 psi (70-100 MPa) [3]. This means that concrete below 10,000 psi (70 MPa) is NSC and above 14,500 psi (100 MPa) is UHSC. Subash Paudel [1] divides concrete according to following ranges, 7250-14,500 psi (50-100 MPa) as high strength, 14500-22,000 psi (100-150MPa) as very high strength, 22,000-29,000 psi (150-200 MPa) as ultra high strength and more than 29,000 psi (200 MPa) as super high strength concrete. According to Jhon Newman [4] a simple definition of high strength concrete would be, “concrete with a compressive strength greater than that covered by current codes and standards”. In

UK it would include concrete with 8700 psi (60 MPa) or more, but in Norway the design code already includes the concrete with strength up to 15,000 psi (105 MPa) as does the forthcoming Euro Code (CEN 2002). Hence this simple definition is not really adequate. He suggested that strength greater than 11,500 psi (80 MPa) be considered as high strength". JSCE designates 8700-14,500 psi (60-100 MPa) as HSC; where as Architectural Institute of Japan designates HSC with design strength more than 5200 psi (36 MPa). JIS A-5308 "ready mixed concrete" termed HSC having nominal strength of 7250 or 8700 psi (50 or 60 MPa). According to ACI committee 7500 Psi (52MPa) considered as high strength in 1960s and 9000 psi (62 MPa) was considered the same in 1970s. The committee also confessed that the definition varies on geographical basis. In regions where 9000 psi (62 MPa) concrete is already in use, HSC might be in the range of 12000-15000 psi (83-103 MPa) [5].

S K Al-Oraimi et al [6] observed that in 1970s 6000 psi (42 MPa) was considered high strength and recently 8700 psi (60 MPa) is considered lower limit for HSC. Wikipedia [7] has also defined HSC having compressive strength more than 6000 Psi (42 MPa). Kangesu et al [8] reported normal high strength concrete 7250-14,500 psi (50-100 MPa) and very high strength concrete 14,500-22,000 psi (100-150 MPa). R. L. Day [9] termed less than 2900 psi (20MPa) concrete as low strength, 3000-8700 psi (20-60 MPa) as normal strength, 8700- 14,500 psi (60-100 MPa) as high strength and more than 14,500 psi (100 MPa) as very high strength concrete.

Two questions arises here, what highest strength of concrete achieved so far, and what maximum can be achieved. Weird.com [7, 10] reported on April 13 2007 that a concrete of 60,000 psi (414MPa) is produced by a team of Tehran University in collaboration with ACI. This was done by using aggregates made from steel fibers and quartz (a mineral with a compressive strength of 160,000 psi (1103 MPa). Much reliable data relating total pore volume and compressive strength is available. Extrapolating this data, when total pore volume is reduced to zero, the compressive strength can theoretically reach 10^5 psi (700 MPa) [5]. Another type of concrete called RPC (reactive powder concrete) can achieve compressive strength values exceeding 87,000 psi (600 MPa). Pierre Richard and Marcel Cheyrezy [11] described that these RPCs have compressive strength ranging from 29,000-116,000 psi (200-800 MPa). RPCs are produced through enhancement of homogeneity by eliminating coarse aggregate. RPC having compressive strength up to 116,000 psi (800 MPa) are produced by using compacting pressure during setting, heat treatment during curing and by adding steel aggregates [11]. Since RPC is without coarse aggregates, it can not be classified like conventional concretes.

Note: 1 MPa = 145 psi (but values are bit rounded off)

3. Strength Classification for Pakistan

It is observed that no specifying limits are available for each class concrete. High strength concrete ranges from as low as 5000 psi (35 MPa) [5] and as high as 14,500 psi (100 MPa) [1]. These classifications are accepted by different researchers according to their own regional requirements. For Pakistan following classification is suggested, based on certain logic described below.

According to S.K. Al-Oraimi et al [6], in normal strength concrete (compressive strength less than 6000 psi (42 MPa)) "the properties of coarse aggregate seldom become strength limiting". According to Odd E Gjorv et al [12], up to compressive strength of about 12,800 psi (90 MPa) the fracture of the concrete is controlled largely by failure of bond between the aggregate particles and the cement paste. For compressive strength above this level, however, it appears that concrete fracture is controlled largely by the strength of rock aggregate. Hence following division deems suitable for strength based concrete classification for Pakistan. Concrete below 6000 psi (42 MPa) may be considered as NSC where fracture is controlled by cement paste, 6000- 12,800 psi (42-90MPa) can be termed as HSC where fracture is largely controlled by the transition zone and above 12,800 psi (90 MPa) it is classified as UHSC where fracture is largely controlled by the strength of aggregate.

3.1 Importance of Aggregate for UHSC

Peitru Lura [13] observed that the strength of concrete is severely influenced by the weakest component; hence strength of aggregate has the major contribution and tends to provide a ceiling for the strength of concrete. S.K. Al-Oraimi et al [6] say the mineralogy and the strength of the coarse aggregate is responsible to control the ultimate strength of concrete. It is also believed that in high strength concrete tensile strength is controlled by mortar strength where as compressive strength is influenced by strength and surface characteristics of coarse aggregate [14]. Concrete comprising weak aggregates will also be weak. Rocks with low intrinsic strength are unsuitable for use as aggregates [15]. Each characteristic of coarse aggregate like specific gravity, bulk density, aggregate impact value and aggregate crushing value has certain influence on ultimate strength of concrete. As discussed earlier, concrete failure can be characterized as paste failure, paste-aggregate bond failure and failure of aggregates. For the first two types of failures there are number of methods available to improve the properties of concrete i.e. if paste is weak it can be made strong by increasing cement fineness, increasing the cement content, reducing water content through use of water reducing agents, using pozzolanic materials and also by improving its density by addition of micro fillers. In addition to its pozzolanic nature silica fumes are very good micro fillers as well. The 15% replacement of the cement mass by silica fumes will add approximately two million particles to each replaced cement grain [16]. The bond failure between paste-aggregate can be avoided by improving the interfacial transition zone (ITZ). Accumulation of water around aggregate particles is one of the sources of ITZ weakness. Use of water reducing agents, viscosity modifiers and improving the grading of constituent materials may help in minimizing this ITZ. Addition of pozzolanic materials like silica fumes, fly ash, GGBS etc. reacts with $Ca(OH)_2$ crystals forming CSH. Silica fume particles consume $Ca(OH)_2$ available in transition zone and makes it dense and uniform[8]. The ITZ can be improved by reducing maximum aggregate size and also by revising mixing sequence. The coarse aggregate is found to be the most important factor for fracture energy. For strong aggregates the cracks run around the aggregate, where as for weak aggregate the crack penetrates and fractures the aggregate [17]. Aggregate must act as crack obstacle. If aggregate itself is failing then its size reduction shall not be of much use and the only choice left is to use the aggregates from another source. Hence, selection of appropriate source of aggregate is much more critical for high strength concretes [4]. Suitability of aggregates is broadly decided on the basis of tests like aggregate crushing value (ACV) and aggregate impact value (AIV). Los angles abrasion value and point load test for rocks are also in use but they are less common. Other tests like sodium sulfate soundness, aggregate angularity and percentage of flat and elongated particles are also important but these are more related to workability/durability rather than strength of concrete. Some good efforts [18-20] have been made to correlate the mechanical properties of aggregates, but a lot of work is yet required to be done before some reliable models are established.

ACV can vary from 5% to 30% (for strong and weak aggregates respectively) [21]. Aggregate strength cannot be easily related to concrete strength [22]. Both ACV and AIV tests give only some indication regarding quality of aggregates. There is no explicit relation between the crushing value and the compressive strength. The crushing value is a useful guide when dealing with aggregates of unknown performance, particularly when lower strength may be suspected [23]. The need of the day is to adopt some other methods to get strength of aggregates which can readily be translated into concrete strength. Authors of "High performance concretes" [24] quoted from Chang and Su, that mean compressive strength of aggregate is calculated as

$$\sigma_{22} = Ph/V \qquad (1)$$

σ_{22} = is mean compressive strength of aggregate.

P = maximum load applied to the single aggregate.

H = distance between the two opposite load points of P.

V = volume of single aggregate determined using Archimedes's principal after the oven dried weight is measured.

It is better that we should adopt/develop some new tests for assessing the proper strength of aggregates. In the absence of some accepted tests we are compelled to rely on the less reliable tests like AIV and ACV. Table 1 gives the properties of Margalla aggregates. The aggregate crushing value is 27.9%, very close to 30, indicating that this aggregate is very week [21]. This table also gives a comparison of the properties of Margalla crush observed in this study with those reported by H Rehman [25] in 1996. It is evident that after about twelve years time there is no appreciable change in the properties of aggregates. Notably the ACV has further reduced by about 1%.

Table: 1 Comparison of Margalla Crush properties

Properties	H Rehman 1996	In 2008
Loose Bulk density	85.95 Pcf	85.29
Rodded bulk density	96.03 Pcf	92.88
Fineness modulus	6.77	-
AIV	17.61%	17.8%
ACV	26.8%	27.9%

4. Experiment

In the present study experimentation is carried out to produce UHSC in the laboratory using Margalla crush. Many mix designs are available in the literature for different concrete strengths. Mix design close to the lower boundary of UHSC was selected. S Bhanja and B Sengupta[26] have given following mix for 13,500 psi (93 MPa). In this study slightly higher binder content is used.

Table: 2 Concrete mix proportions

	S Bhanja Mix	Present study
Cement	468 Kg/m^3	472.5 Kg/m^3
Silica Fume	52 Kg/m^3	52.5 Kg/m^3
Fine Agg.	667 Kg/m^3	667 Kg/m^3
Coarse Agg.	1146 Kg/m^3	1146 Kg/m^3
W/C Ratio	0.26	0.26
SP	3.5 %	3.5 %

Materials used are locally available Maple leaf cement of 42.5 MPa class (Manufacturer's Note: Clinker 95%, gypsum 5%, strength up to 5800 psi). Lawrencepur sand having 2.69 FM, Margalla crush of half inch down size, Cormix SF1 silica fume and Chryso Fluid Optima (Glenium 51) super plasticizer supplied by Cormix International. Margalla crush has following gradation, retained on 0.5 in 0 %, 3/8 in 52.5% and 3/16 in 47.25%.

Using conventional 6x12 in (150x300 mm) concrete cylinder are uneconomical, contents of UHSC like cement (high content is required) silica fumes and super plasticizers are very costly. Moreover handling of 14-kg specimen is difficult and can lead to injuries [27]. Many researchers used smaller samples [8, 9, 27-29]. R J Detwiler is trying hard for acceptance/standardization of smaller samples. Recognizing her efforts, ACI Code 318-08 allowed the use of 4x8 in (100x200 mm) cylinders in lieu of 6x12 in (150x300 mm). Obviously there would be strength increase due to size effect, but ACI code did not specified any correction factor in this regard. Authors of recently published book on Structural Concrete [30] had mentioned a vide range of relative strength co-efficients. These co-efficients are taken from US bureau of reclamation concrete manual 7th edition 1963. On the other hand V Kadlecek et al [28] suggested some size related co-efficients, which are quite different from US Bureau. In 1963 concrete technology was not as advanced, hence these factors are required to be re-evaluated. ASTM C31-03 allowed the use of 5x10 in (125x250 mm) and 4x8 in (100x200 mm) cylinders for other than acceptance testing with the limitation that the diameter of any cylinder shall be at least three times the nominal maximum size of the coarse aggregate. However ASTM C 31/C 31M – 06 permitted 4 in (100mm) dia cylinders even for acceptance testing.

In the present experimentation the maximum size of aggregate is 0.5 in (12.5 mm), hence minimum dia of cylinder which can be used according to ASTM C31-03 is 1.5 in (38 mm). However for the purpose of present study, three type of cylinders 3 in (75x150 mm), 2.5 in (63x125 mm) and 2 in (50x100 mm) were used to study the effect of specimen size. Height to diameter ratio is kept equal to 2 as per standard specifications to allow the similar slenderness effects. Cubes of 4x4x4 in (100x100x100 mm) were also casted for comparison purposes. To prevent moisture loss, specimens were covered with polyethylene sheet immediately after casting. Specimens were de-molded after 48 hours and then placed in water for moist curing. These were removed from water one day before testing and placed in the open air for drying. Testing was carried out for 7, 14, 28 and 56 days. After casting two batches using above mentioned mix proportions, it was observed that strength is much less than the targeted strength. To improve the ITZ for the purpose of strength enhancement, w/c ratio was further reduced to 0.24 and the aggregate size was also further reduced. Now maximum aggregate size used was 3/8" instead of 1/2". Another two batches revealed that further improvement in the strength is not possible, hence experimentation was discontinued. 1st set of casting is designated as Mix (1/2-0.26) and 2nd as Mix (3/8-0.24).

5. Discussion on Experimental Results

Test results for compressive strength of 4 in (100mm) cubes are presented in figures 1 & 2, and that of 2, 2.5 and 3 in (50, 63 and 75mm) dia cylinders are presented in figures 3 & 4.

Tensile strength measured using split cylinder test based on 2, 2.5 and 3 in (50, 63 and 75mm) diameters is presented in figure 5, and overall picture is shown in Fig. 6.

5.1 Strength Development Trends

From all the above figures it is evident that when aggregate strength is exhausted then there is no satisfactory model available to predict the strength of concrete. Mix (1/2—0.26) shows decrease in strength with time. This trend is unusual in the normal strength concrete. This is because up to certain limit when all the components of concrete have comparable strengths concrete gain appreciable strength. When after the start of pozzolanic activity the matrix become stronger than the aggregates, the aggregate along with ITZ becomes the weakest part of the concrete. The weak crystals of $Ca(OH)_2$ after reacting with silica fume produce CSH which starts building pressure on the aggregate. This mounting pressure with time is responsible

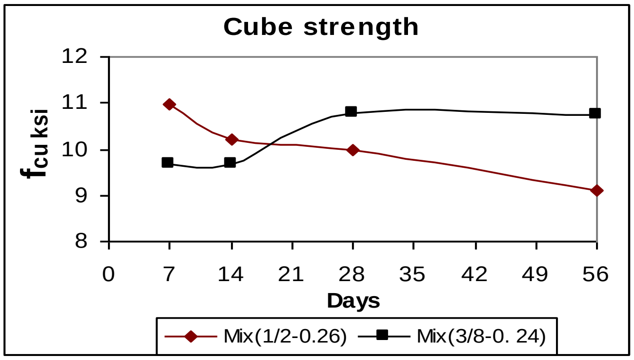

Fig.1 Cube strength comparison

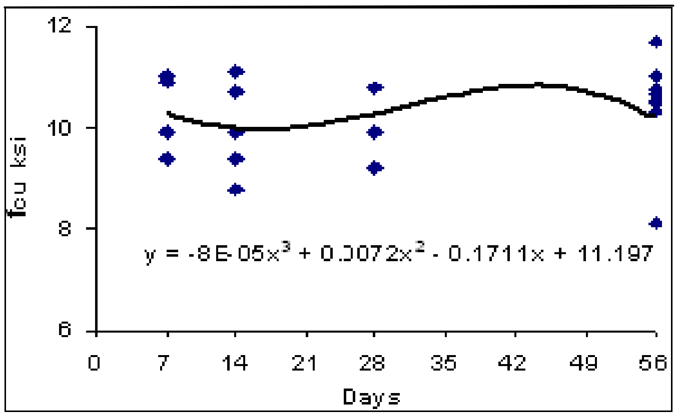

Fig. 2 Overall strength development trend

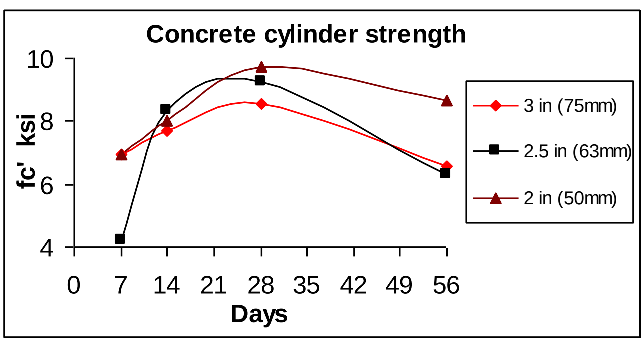

Fig. 3 Concrete cylinder strength

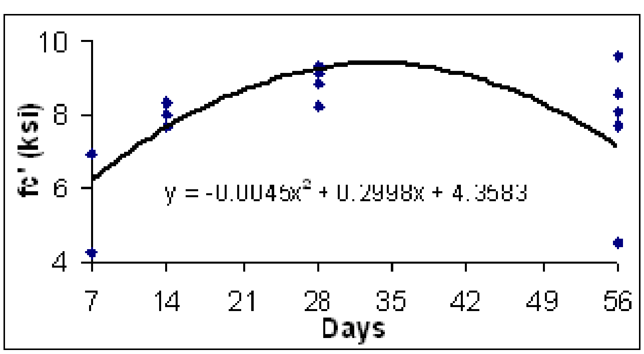

Fig. 4 Overall fc' development trend.

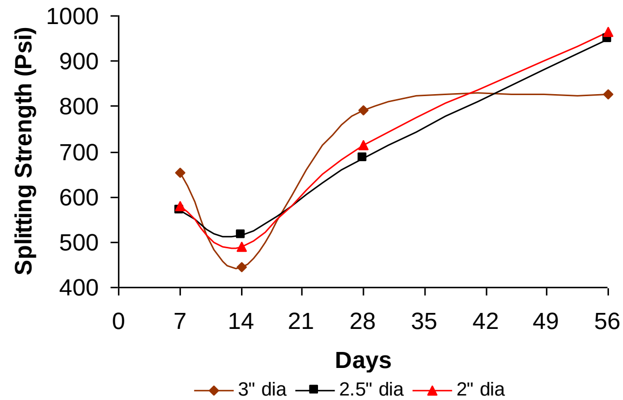

Fig. 5 Split Cylinder Strength

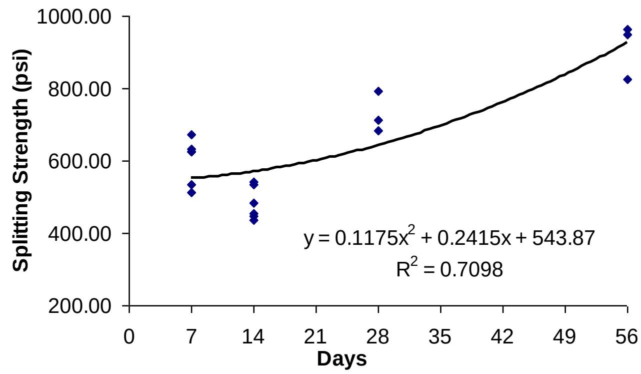

Fig.6 Overall split cylinder strength development trend.

for failure of aggregate even on lesser external loads. On the other hand the mix (3/8—0.24), where size of aggregates and w/c ratio was reduced in order to improve the characteristics of ITZ, shows little bit increase in the strength with no appreciable gain. Moreover a slight downward trend is present after 28 days. This indicated that improved ITZ provide certain relief to aggregate but after 28 days this relief is exhausted and internal pressure compels aggregates to fail under lower external load. This fact is also clear from figure-2 where combined effect of both the mixes is presented. Even the best fit 3rd degree polynomial gives R^2 values close to zero indicating very poor correlation for strength development with age.

The compressive strength of cylinders (figure 3) also shows similar trend. For all three types of cylinders strength increased up to 28 days and then it started decreasing. Reason is same that the pozzolanic reaction in the ITZ builds internal pressure on the aggregates which reduces the external load required for aggregate failure. Overall trend is shown in figure-4. The 3rd degree best fit polynomial is better than that of cube strength, but R^2 value is far less than unity indicating again a poor correlation.

The split cylinder strengths are presented in figures 5 and 6. At the 1st glance trend of tensile strength seems to be opposite of that observed for compressive strength, where strength first increases and then starts declining with age, where as tensile strength first decreases and then starts increasing after 2 weeks. The reduction in compressive strength, and increase in tensile strength after few weeks is due to the same reason as explained earlier. When the calcium silicate hydrate starts filling the pores and exerts pressure on the aggregates causing reduction in the volume of aggregate (which starts acting as void when strength of matrix exceeds that of aggregate). These compressed aggregates absorb some external load and subsequently failing in tension. As the internal pressure increase with age, the tensile strength also exhibits an upward trend. The overall relation based on 2nd order best fit polynomial is showing an upward trend. The R^2 value though not very close to unity but is fairly acceptable.

5.2 Role of Aggregate Mechanical Properties

Very limited data is available regarding relationship between mechanical properties of aggregates and compressive strength of concrete. I H Zarif and A Tugral [19] postulated the following linear relation between ACV and $\boldsymbol{\sigma}_{\mathbf{c}}$ (un-confined compression strength)

$$\text{ACV} = 21 - 0.04\boldsymbol{\sigma}_{\mathbf{c}} \qquad (2)$$

This relation may be true for the particular lime stone from Istanbul, but it can’t be accepted as general formula. This equation gives zero compressive strength for ACV equal to 21 and negative for larger values, which is not practically possible.

Al-Harthi [18] proposed two relationships between ACV and UCS (un-confined compressive strength).

$$\text{ACV}(\%) = \exp(3.71 - 0.005\text{UCS}) \qquad (3)$$

$$\text{ACV}(\%) = 78.82 - 11.73 \ln(\text{UCS}) \pm 2.69 \qquad (4)$$

Equation 1 gives average values and equation 2 gives range of values in between which UCS can vary. For Margalla crush equation 1 gives value equal to 11,000 psi (76 MPa), and equation 2 gives strength 8800 to 14,000psi (61 to 96 MPa). The measured strength of Margalla crush concrete is almost falling within this range, the actually measured strength range is 8120 to 11,709 (56 to 81 MPa). The slight difference between measured and expected strength range is due to the involvement of densification/ hydration stresses which reduce the strength of aggregates. This fact is not yet properly addressed by any one, but some researchers had given some indications which points towards these criteria. Hiroshi et al[31] reported densification of concrete from the age of 28 days, where as K Y Liao et al [32] and A Loukili et al [33] reported that at the age of 14 days the pores were filled due to pozzolanic reaction and porosity was quickly reduced at the age of 28-56 days. Exactly the similar trend is observed that the compressive strength of concrete prepared from weak Margalla aggregates starts reducing after age of 28days. P Acker [34] observed that due to C-S-H gel the sign of strain rate changes between 10 to 20 days and after that it swells. At the age of 28 days high strength concrete is strong enough that its free swelling is not possible, hence it will result in increased internal stresses. P Acker also concluded that the C-S-H gel is essentially subject to a tri-axial stress field of a *deviatoric* nature, and the gel is primarily subject to shear forces.

Pietro Lura [13] conducted experiments on lightweight aggregates and his observation period was limited to 13 days. He noted that there was a slight relaxation up to 3 days and then an increase in internal compressive stress continues up to 160 psi (1.1 MPa). These are the results with LWA. Had he used the normal weight aggregates along with silica fume, the developed compressive stresses may be higher. Another interesting phenomenon is described by S Miyazawa et al [35]. They reported that gain in mass occurred because specimen absorbed water into capillary pores. He also observed, “the self stress caused by restrained autogenous volume change can be large and should be taken into account when designing high strength concrete structures”.

Olivier Bernard et al [36] identified two types of C-S-H gels, i.e. low and high density. High density gel is formed in a space confined by the existing low density gel. It is believed that initially low density gel is formed in the ITZ. As densification progressed the region between aggregate and low density is packed with high density gel exerting compressive stresses on aggregate. G W Scherer [37] indicated that for a crystal growing in a pore, it is the pore wall that applies stress to arrest the growth. The hydration of cement results in crystallization pressure of about 850 psi (6 MPa), which dominates the capillary pressure.

6. Conclusions

The size effect law of fracture mechanics may be applied to brittle materials like concrete. This law is very complex but it can be simply represented by the following relation [38].

$$\sigma_N = \frac{B.f'_t}{\sqrt{1+d/d_o}}$$

Where f'_t is direct tensile strength, B and d_o are empirical constants and d is characteristic dimension of the specimen or structure. This shows that a smaller specimen is likely to give more strength. The strength of 3 in (75mm dia) cylinder must be less than the other two, but this trend is not exactly followed throughout the whole range of test results. In-fact, when strength of concrete is controlled by the aggregates, then instead of following the fracture mechanic laws, with weak matrix strong aggregate concept, the concrete acts as a strong matrix containing large number of weak aggregates/voids. The strength of specimens depends upon the number of voids present and their distribution along the failure plane.

When the aggregate is weaker than the surrounding matrix, then all strength prediction models for concrete should mainly depend on the properties of the aggregates.

ACV and AIV values are indicative indices of aggregate strength. No acceptable relation exists between ACV and strength of concrete. Some new test indicating aggregate strength in concrete is required to be developed. Correlation between aggregate strength and concrete strength is required to be established.

Margalla crush is not suitable for UHSC, rather it should not even be recommended for HSC.

Though above 9000 psi (62 MPa) concrete strength has been achieved in the laboratory using Margalla crush, but due to presence of uncertainty, these aggregates should be used for construction where required cylinder strength does not exceeds 6000 Psi (42 MPa).

7. Recommendations

As pointed out by K Y Liao et al [32], due to experimental difficulties, the information about the filling effect of hydration products on transition zone is scarce. Much work had been carried out pertaining to reaction kinetics of cement hydration but the resulting stresses developed by this hydration are still unknown. The present study was not aimed at finding hydration pressures, but the strange results attracted attention in this direction. This is high time that extensive experimentation be carried out using sophisticated stress measuring devices/data acquisition systems (these facilities are not available in Pakistan). To start with, a very simple relation can be assumed as

$$f_c' = f_a' - f_h \tag{6}$$

Where f_c' is concrete crushing strength, f_h is hydration stresses on aggregate and f_a' is actual concrete strength. It means

$$f_a' = f_c' + f_h \tag{7}$$

The actual concrete strength is greater that the conventional f_c'. Care must be taken in applying this model for finite element modeling/simulation as this model shall work only for weak aggregate and strong matrix. For weak matrix and strong aggregates different/opposite results are expected.

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References

[1] Subash Paudel, development of very high strength concrete "the art of an engineer" Sep 2006. ww.teamcec.com/TB0906.html Accessed on 20th sep 2008.

[2] E Limsuwan, P Haleerattanawattana, strength-based gradation for mix design of ultrahigh strength concrete, Conf. Proc. ACBM-ACI Lahore-Pakistan, 12-14 Dec.2007, Vol. 1, pp. 355-362.

[3] L T Phan, N J Carino, Code provisions for high strength concrete strength-temperature relationship at elevated temperatures, Materials and Structures, Vol. 36, No. 256, 91-98, March 2003.

[4] Bill Price, High strength concrete. In: J Newman, B S Choo, editors. Advanced concrete technology (processes). Elsevier Ltd.(2003). ISBN 0 7506 5105 9

[5] State of the art report on high strength concrete in japan recent developments and applications, www.jsce.or.jp/committee/concrete/e/newsletter/newsletter05/7-Vietnam%20Joint%20Seminar%20(Kawai).pdf, accessed on 25th May 2009.

[6] S.K. Al-Oraimi, R. Taha, H.F. Hassan, The effect of the mineralogy of coarse aggregate on the mechanical properties of high-strength concrete, Construction and Building Materials 20 (2006) 499–503.

[7] Wikipedia, the Free Encyclopedia, http://en.wikipedia.org/wiki/Concrete, accessed on 30th may 2009.

[8] K Vivekanandam, I Patnaikuni, Transition zone in high performance concrete during hydration, Cement and Concrete Research, Vol. 27. No. 6, pp. 817-823.1997

[9] R L Day, Strength measurement of concrete using different cylinder sizes: A statistical analysis. Cement, concrete, and aggregates, CCAGPD, Vol. 16, No. 1, June 1994, pp. 21-30.

[10] D Hambling, Iran's Invulnerable Bunkers, posted on April 13, 2007, http://www.wired.com/dangerroom/2007/04/irans_superconc/ Accessed on 30th may 2009.

[11] P Richard, M Cheyrezy, Composition of reactive powder concretes, Cement and Concrete Research, Vol. 25. No. 7, pp. 1501-1511.1995.

[12] O E Gjorv, T Bearland, H R Ronning, Abrasion resistance of high strength concrete pavements, Concrete International, Jan. 1990, PP. 45-48.

[13] Pietro Lura, Internal water curing with Liapor aggregates, HERON, Vol. 50, No 1 (2005)

[14] T Dzturan, C Ceqen, Effect of coarse aggregate type on mechanical properties of Concretes with different strengths, Cement and Concrete Research, Vol. 27, No. 2, pp. 165-170, 1997

[15] http://www.understanding-cement.com/strength.html, accessed on 20th June 2009.

[16] G C Isaia, A L G Gastaldini, R Moraes, Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete, Cement & Concrete Composites 25 (2003) 69-76

[17] FHWA-RD-00-161, June 2001, The effects of higher strength and associated concrete properties on pavement performance, U S department of transportation, pp. 30.

[18] A A Al-Harthi, A field index to determine the strength characteristics of crushed aggregate, Bull Eng Geol Env (2001) 60:193-200.

[19] I H Zarif, A Tugrul, Aggregate properties of Devonian limestones for use in concrete in Istanbul Turkey. Bull Eng Geol Env (2003) 62:379–388

[20] A A Al-Harthi , Y E Abo-Saada, Wadi natural aggregates in western saudi arabia for use in concrete, Bulletin of the International Association of engineering geology, Paris No. 55 – April 1997.

[21] M A Kamal, M A Sulehri, D A B Hughes, Engineering characteristics of road aggregates from northern Pakistan and the development of a toughness index, Geotechnical and Geological Engineering (2006) 24: 819–831.

[22] P Zhou, F D Lydon, B I G Barr, Effect of coarse aggregate on elastic modulus and compressive strength of high performance concrete, Cement and Concrete Research, Vol. 25, No. 1, pp. 177-186.1995.

[23] A M Neville, Properties of concrete, 3rd edition, ELBS/Longman (1981).

[24] P Zia, S Ahmad, M Leming, High-performance concrete: A state-of-art report(1989-1994), FHWA-RD-97-030, U S department of transportation, pp.17.

[25] H Rehman, Analysis of research on shear strength of rectangular reinforced concrete beams, M Sc thesis, Civil Engg. department UET, Lahore, Pakistan. March 1996.

[26] S Bhanja, B Sengupta, Water-cement ratio law and silica fume concrete mix design. In: R K Dhir, T A Harrison, M D Newlands, editors. Proc. of intl. conference, "Cement combinations for durable concrete" UK 5-7 july 2005, pp. 107-112.

[27] R J Detwiler, Acceptance testing for concrete using 100-mm x 200-mm Cylinders, Conf. Proc. ACBM-ACI Lahore-Pakistan, 12-14 Dec.2007, Vol. 1, pp. 107-111.

[28] V Kadlecek Sr., S. Modry, V Kadlecek, Jr. Size effect of test pecimens on tensile splitting strength of concrete: general relation, Materials and Structures, Vol. 35, January-February 2002, pp 28-34.

[29] R L Day, M N Haque, Correlation between strength of small and standard concrete cylinders, ACI Material Journal, Title no.90-M48, Vol. 90, No. 5, Sep-Oct. 1993

[30] M N Hassoun, A Al-Manaseer, Structural Concrete theory and design, 4th edition, Jhon Wiley & Sons, INC. (2008)

[31] H Uchikawa, S Hanehara, H Hirao, Influence of microstructure on the physical properties of concrete prepared by substituting mineral powder for part of fine aggregate, Cement and Concrete Research. Vol. 26, No. 1, pp. 101-111, 1996

[32] K Y Liao, P K Chang, Y N Peng, C C Yang, A study on characteristics of interfacial transition zone in concrete, Cement and Concrete Research 34 (2004), PP. 977–989

[33] A Loukili, A Khelidj, P Richard, Hydration kinetics, change of relative humidity, and autogenous shrinkage of ultra-high-strength concrete, Cement and Concrete Research 29 (1999), pp. 577–584

[34] P Acker, Swelling, shrinkage and creep: a mechanical approach to cement hydration, Materials and Structures / Concrete Science and Engineering, Vol. 37, May 2004, pp 237-243.

[35] S. Miyazawa, P J M Monteiro, Volume change of high-strength concrete in moist conditions, Cement and Concrete Research, Vol. 26, No. 4, pp. 567-572, 1996.

[36] O Bernard, F J Ulm, E Lemarchand, A multi-scale micromechanics-hydration model for the early-age elastic properties of cement-based materials, Cement and Concrete Research 33 (2003) 1293–1309.

[37] G W Scherer, Stress from crystallization of salt, Cement and Concrete Research 34 (2004) 1613–1624

[38] ACI Committee Reports, ACI-446.1R-91 Reapproved 1999, and ACI-224R-01, May 16, 2001.