American Journal of Engineering Research (AJER)
E-ISSN: 2320-0847 p-ISSN: 2320-0936
Volume-8, Issue-1, pp-172-183
www.ajer.org
Research Paper Open Access

Role of water/binder ratio on strength development of cement mortar

Amr ElNemr[1,*]

[1] *Assistant Professor in Material Engineering at Civil Engineering Department, German University in Cairo (GUC), Egypt, E-mail: amr.elnemr@guc.edu.eg. *(Corresponding author)*

ABSTRACT*; In this paper, influence water/binder ratio on the hardened state properties of cement mortar was investigated after 28 days curing period as assigned by ACI Standard. From the results, empirical equations have been generated evaluating the strength of cement mortar mixes with various water / binder ratios. It was deduced that Abram's law is valid for most of cement mortars established. The cement mortar consists of ordinary Portland cement with 15% partially replacement by silica fume, fine aggregate (sand) with varying portions of 1:3, 1:4, 1:5, 1:6 and different water binder ratios ranged from 0.4 to 0.8. From results, a relationship between split tensile strength and compressive strength of cement mortar has been reached. Furthermore, it was observed, from the results; that a reduction in compressive and tensile strength of cement mortar, while, increasing the water-to- binder ratio higher than 0.5 in case of cement: sand of 1:3. While, this effect was deduced at water-to binder ratio of 0.7 when using cement: sand of 1:4, 1:5, and 1:6. It is concluded that the optimized water –to–binder ratio required for achieving workable cement mortar was mainly based on cement: sand portions.*

CE Database Subject Heading: *cement; mortar; silica fume; water –to- binder ratio; compressive strength; tensile strength.*

Date of Submission: 05-01-2019 Date of acceptance: 22-01-2019

I. INTRODUCTION

Growth of developing countries rely mostly on the energy. The demand to save energies consumed by materials manufacturer such as those of steel and cement etc. increases by indigence inquiry to reduce these non-reversible energy. In this sense, the world trend have in sighted the importance of recycling the industrial wastes for use in construction field. Cumulative large amount of by products and / or industrial wastes lost without any use each year (Gowri et al. 2016). But still the efficiency of using these wastes is in question. Though, the natural resources will be saved and influenced sustainability, for instance; concrete industry encouraged the use of mineral admixtures which are By-products of other industries. Thus, in today's concrete manufacture, the introduction of industrial by product reduces the negative impact initiated by concrete on environment.

One of these materials is the silica fume consisting of silicon or ferrosilicon alloys resulted from amorphous form of silicon tetrachloride combusted by hydrogen-oxygen flame. Several researchers (Sharp 1944, Holland et al. 1986, Whiting and Detwiler 1988, Gee et al. 1994, Thomas et al. 1999, Wild et al. 1995, Holland 2005, Buhler 2017) investigated the use of the silica fume in concrete mix and discovered their enhancement to the concrete properties. Binding materials play an important role in the quality, durability and strength of the cement mortar.

Yogendran et al. (1987) investigated the addition of silica fume through experimental program. The design of mixes assigned, in this experimental program; to maintain high strength concrete. The authors observed a high increase in compressive strength and significant reduction in slump even though with the addition of super plasticizer by approximately 0.75% on average. On the other hand, Hootan (1993) has investigated both physical and durability properties such as cyclic freezing and thawing, sulphate attack and alkaline silica reactivity; when silica fume partially replaced cement in a concrete mix. It was deduced that 28 days compressive strength was maximized when replacing 15% of cement with silica fume. It should be mentioned that author added variable dosage of superplasticizer as water – to – binder ration equal 0.35.

Shreekedar and Kumbhar (2013) have studied the mineral admixture and its influence by high performance concrete. They replaced cement with micro silica adding super plasticizer to the mix for more workability. They observed that better strengths were achieved at 15% replacement. Recently, Hunchate et al. (2014) have investigated the high performance concrete by using mineral admixtures such as silica fume. The study included several percentage of replacement; 0, 5, 10, 15, 20, and 25%. The water-to-binder ratio considered was equal to 0.29. It should be mentioned that the aging factor was considered as testing the cubes on both 7 and 28 days. From the results, they deduced that as silica fume content increases; the compressive strength increases. This behavior continues until reaching 15% replacement, however; after 15% replacement, the compressive strength reduces, eventually. It was noted that as the silica fume replacement increases, the workability decreases. It should be noticed that few investigation studied the influence of cement: aggregate either coarse or fine or even both.

Historically, in concrete technology, Abram's formula was the first one describing the dependence of concrete strength on water-to-cement ratio (Duff, 1918). In fact, Abrams suggested a formula that represents a relationship between concrete strength and water-to-cement ratio. The formula as seen generalized the inversely effect of water-to-cement ratio on compressive strength (Singh et al. 2015). The formula is as follow:

$$Strength = \frac{K_1}{K_2^{\frac{w}{c}}} \qquad (1)$$

Where K_1 and K_2 are constants, w represents mass of water and c assigned for the mass of cement. The validity of this formula was proven above water-to-cement ratio ranges from 0.3 to 1.20 for an average Portland cement concrete cured under normal temperature and moisture. Oluokun (1994) had deduced using Abrams relationship between strength and water-to-cement ratio both constant coefficients K_1 and K_2 were evaluated through his investigation at different aging of 7 and 28 days. The following **Equation 2** presents the resultant of the estimated coefficient; K_1 and K_2:-

$$f_{c7} = \frac{63.45}{14^x} \quad and \quad f_{c28} = \frac{96.55}{8.2^x} \qquad (2)$$

Where, f_{c7} and f_{c28} represent the strengths in MPa at 7 and 28 days, respectively, while, x represents the water-to-cement ratio. Rao (2001) had suggested an empirical equation that can estimate the compressive and split tensile strength of mortar through determining the water – to – cement ratio. The equation was limited to water – to – cement ratio greater than 0.4 and mainly rely upon Abram's law. On the other hand, Yeh (2006) have studied the aging influence on Abram' law. He encountered the validity of Abram's law at many different ages' ranges from 3 to 365 days. Generally Rao (2001) had deduced that several other parameters affect the mechanical properties of the cement mortar such as water – to – cement ratio, cement – to - sand ratio, types of cement material and finally the aggregate characteristics.

Many studies (Tamilarasan and Perumal 2012, Yatagai et al. 2010, Pavia and Condren 2008, Barnett et al. 2006, Khan and Ghani 2004, Wild et al. 1995, Oluokun 1994) have investigated the addition of mineral admixtures into concrete mix. Though to consider the encountering of mineral admixtures while mix design; the water-to-cement ratio was replaced by water-to-binder ratio instead. Thus, the strength prediction becomes more accurate (Babu et al. 1996, Oluokun 1994). Consequently, the water-to-binder ratio was formulated as following (Metwally, 2014):

$$x = \frac{w}{c + kf + s} \qquad (3)$$

Where x assigned for water-to-binder ratio; w, c, and f represented water, cement and fly ash content; in addition, s donated for granulated blast furnace slag (GBFS), while, k symbolized an efficiency factor. Duff (1918) suggested the development of power formula, to the Abram's laws which is originally related the water – to – cement ratio with compressive strength of concrete. The formula takes the following shape:

$$f_{c,t} = \frac{A_t}{B_t^x} = A_t * B_t^{-x} \qquad (4)$$

Where, **Equation 4** is similar to that of **Equation 1** with subscript (t) indicating age at (t) days; usually 28 days. Yeh (2006) generated a power formula for estimating compressive strength at any given age without collecting data at that age. This was developed by using parameter trend methods such as regression and four parameter optimizing methodology to identify this relationship.

Metwally (2014) stated that the implementation of either Abram's formula or power formula to predict the concrete strength at any age requires collecting of huge data at that age, then developing a specific formula using the time factor (age function) as a function in specific age strength (usually – 28 day strength) to estimate the strength at a given age.

Although all these data upon formulating the relationship between water-to-cement ratio and compressive strength, it still not applicable when adding mineral admixtures. Many researchers (Oluokun 1994, Wild et al. 1995, Babu et al. 1996, Sear et al. 1996, Rao 2001, Han and Kim 2004, Yeh et al. 2006, Barnett et al. 2006, Pavia and Condren 2008, Yatagai et al. 2010, Parniani et al. 2011, Rajamane and Ambily 2012, Tamilarasan and Perumal 2012, Singh et al. 2015, Gowri 2016) studied and investigated the optimum percentage of adding mineral admixtures, however, nearly no one formulated an empirical equation for specified percentage at specified age to determine the corresponding compressive and splitting tensile strength.

Thus, the objective of this paper is to determine the influence of water-to-binder ratio on the cement mortar's mechanical properties such as compressive and split tensile strength, while examining the validity of the Abram's law for cement mortar at specified percentage of replacement; 15% of silica fume. Furthermore, empirical equation are developed to predict the strength of cement mortar for different water-to-binder ratio as well as different binder-to-fine aggregate ratio.

II. RESEARCH SIGNIFICANCE

A wide variety of wastes available and encourage to be encountered through the construction industry. The mineral admixtures such as silica fume, fly ash and granular blast furnace slag etc. were widely investigated. From the researchers' results (Sharp 1944, Holland et al. 1986, Whiting and Detwiler 1988, Gee et al. 1994, Thomas et al. 1999, Wild et al. 1995, Holland 2005, Buhler 2017), an optimum of 15% cement replacement was deduced to enhance the hardened state of concrete with water –to- binder ratio of 0.35. The validity of Abram's law presenting the relation between water-to-cement ratio and the compressive strength of concrete as well as cement mortar were extensively studied and ensure estimating the compressive strength at 7, 28 till 365 days. However, nearly no researchers observed the water-to-binder ratio and its relation with compressive strength. Thus, the significance of this paper is to determine the influence of water-to-binder ratio when using silica fume on the cement mortar's mechanical properties and specify the validity of the Abram's law for cement mortar at specified percentage of cement replacement; 15% of silica fume. Furthermore, empirical equation are developed to predict the strength of cement mortar for different water-to-binder ratio and different binder-to-fine aggregate ratio.

III. EXPERIMENTAL PROGRAM

Material and mix design

In this study, several mixes including silica fume with various water –to – binder ratio were prepared to investigate its influences on strength of cement mortar. The materials used to prepare the mixes includes ordinary Portland cement, silica fume, and fine aggregate. **Table 1** and **2** shows physical and chemical characteristics of Portland cement. For fine aggregate used in this study such as sand, sieve analysis and practical size distribution were carried out; as shown in **Figure 1**. It should be mentioned that the characteristics of fine aggregate was identified by laboratory testing while silica characteristics was provided by manufacturer SIKA Inc., Egypt as presented in **Table 3**. The experimental program induced four mixes with varied cement: sand proportions (1:3, 1:4, 1:5, and 1:6) and several water – to- binder ratio ranges from 0.4 -to- 0.80. The four mixes were mixed using Hobart for 2 to 3 minutes. Then after, the molds of cubes and cylinder specimens were prepared via cleaning and painting the interior surface with release agent (oil). It should be ensured that the oil is spreaded all over the interior surface of the molds using clean brush. The mortar of four mixes were cast into three cubes of dimension 100 x 100 x 100 mm and six cylinders of diameter 100 mm and height of 200 mm specimens. It should be stated that the mortar was cast into several layers each was compacted via trowel rod with 25 standard blows. Then after, the final layer; the molds were placed on a vibrating tables to ensure fully compaction of mortar. The specimens were left for 24 hours at room temperature to achieve its setting. Consequently, the specimens were removed from the molds and cured by submerging in curing tanks. The specimens were then left for 28 days inside the curing tanks.

Experimental tests and procedure

The two main aspects that affect the determination of mechanical properties or hardened state properties of cement mortar are the compression and split tensile strengths. Three cylinders and cubes were examined for each mix using Universal Testing Machine. Aging is usually one aspect that influences the results of both compression and split tensile strengths. Thus, a constant 28 days aging was considered for the four mixes. The tests were held according to ASTM C 39 for compressive strength of cylinders and BS EN 12390-3 (2009) for compressive strength of cubes. While, for splitting tensile strength, ASTM C 496 was adopted.

After 28 days of curing, the samples were dried out of the tank and the cubes as well as the corresponding cylinder were tested for the load they can endure before failing. **Figure 2** presents the cube specimen set up in compression loading machine along with the failure mode of mentioned cube specimens. For each mix, 3 compressive cubes and 6 cylinders (3 cylinders for compression testing and the other 3 are splitting cylinders for splitting tensile strength) were tested to evaluate the compressive and tensile strengths. This involves a various water-binder ratios ranges from 0.4 –to- 0.8. When measuring the cylinders, the specimens were placed to be in contact of the bearing surface of the universal testing machine, as shown in **Figure 3.** To determine the compressive strength of the cubes, the UTM loading was adjusted at a rate 240 kgf/s till the failure of the specimen. However, when testing the cylinders specimens for splitting, the specimens were placed in contact along the length of the cylinder, see **Figure 6**. Accordingly, the UTM loading rate was adjusted at a value of 94 kgf/s while measuring the tensile splitting strength. Then after, compressive and tensile strength results were reported.

Figures 2 and **7** show typical mode of failure for both cubes and cylinder specimens under compression and tensile split loading. It should be mentioned that the splitting tensile strength is indirect method for simulating the direct the tensile loading on concrete which is too difficult to be performed in reality. Thus, the maximum tensile stress when using the splitting tensile loading method can be calculated as seen from **Equation 5.**

$$f_{ct} = \frac{2P}{\pi dl} \qquad (5)$$

Where, P is load applied to the specimen; l, d is the length and the diameter of the specimen, respectively, finally, f_{ct} is the split strength.

Optimum water content

It is necessary to verify the optimum water-to-binder ratio required for cement mortar and fully exploit its mechanical properties. It is very important to validate the required optimum water – to – binder ratio required for cement mortar and fully explore its mechanical properties. Thanh (1991) had developed a relationship between the cement and the fine aggregate weights to evaluate the amount of water required in mortars according to two hypothesis. The first hypothesis is based on determining the amount of complete hydration process of cement. The second hypothesis relay mainly on the amount of water required for lubricating the fine aggregate particle, sand; in covering up its specific gravity. This relationship was formulated as shown in **Equation 6**

$$m_w = m_a w_a + m_{cm} w_{cm} \qquad (6)$$

Where m_w is the optimum mass of water, m_a and m_{cm} are the mass of aggregate and cement, respectively; while, w_a and w_{cm} are fractions. The fractions, w_a, was assessed by the specific surface of the sand, while, w_{cm}, for cement was taken by constant value. The range of w_a was around 0.08 –to- 0.11 for specific surface ranges from 3.2 to 8.2 m^2/Kg. on the other hand, the w_{cm}, was taken by value of 0.21.

Consequently, the same equation was adopted, here in this study, where the w_{cm}, was used for binder (cement + silica fume) and taken by the same constant value. The silica fume was added to the equation via the weight of cement. After calculating the weight of cement, the weight of silica was calculated by dedicating 15 % of the weight of cement. This percentage, as mentioned previously, the optimum percentage used by researchers (Sharp 1944, Holland et al. 1986, Whiting and Detwiler 1988, Gee et al. 1994, Thomas et al. 1999, Wild et al. 1995, Holland 2005, Buhler 2017) to get the highest compressive strength. Accordingly, the optimum water content required for the various cement: sand ratios (1:3, 1:4, 1: 5, and 1:6) are assessed by 0.46, 0.54, 0.63, and 0.72 of water –to- binder ratios, respectively. From the test results, the compression and split tensile strengths are maximum at water –to- binder ratio of approximately 0.5 for cement mortar of 1:3, and 0.7 for cement mortar of 1:4 and 1:5, finally, 0.6 for cement mortar of 1:6.

IV. TEST RESULTS AND DISCUSSION

Compressive strength

60 Cubes of 100 x 100 x100 mm in dimensions and 60 cylinders of 100 mm in diameter and 200 mm in height were cast and tested in compression. The results of compressive strength for cube and cylindrical specimens including the difference and coefficient of variations (% COV) are presented in **Table 4**. It is observed that the ratio of compressive strength of 100 mm diameter cylinder to compressive strength of 100 mm cube is valued by 0.86 on-average. From the results, it is deduced that the strength increases with water quantity till a ratio of 0.7 when using cement – binder: sand greater than 1:3. This could be attributed to the adequate hydration process in which the cement paste encounters while increasing the water content. In contrast, very low water content, initially; results for improper fully hydration process which lowered the strength in cement

mortar. In addition to the subsidization of the silica fume for cement requires higher water content for workable and flow able cement mortar reducing the number of pores which influences the strength, instantaneously.

Logically, subsequent addition of water leads to reduction in strength as expected. Various failure patterns of specimens under compression tests are shown in **Figure 2**. The initial cracks were generated from the top of the cube and propagated to the bottom as the load increases. Then, the cracks width have grown at failure along the edge of the cube, as shown in **Figure 2**. Abram's law proven validity at high strength mortar were the water –to- binder ratio is greater than 0.40. After reporting the results and plotting the graphs, it has been noticed that compressive strength of cement mortar shifted the flow of Abram's law, as clear in **Figure 5**.

Figure 5 depict the point at each of the four mixes representing the relationship between predicted compressive strength and water –to– binder ratio. This is attributed to the high fine aggregate to binder (cement + silica fume) content in the three mixes (1:4, 1:5 and 1:6). Thus, the compressive strength of higher values at the water – to – binder ratio of 0.7. While, the only mix (1:3) where the water – to – binder ratio of 0.5 represented the high compressive strength following the Abram's law when using Ordinary Portland Cement alone. This means that more water is necessity to ensure the fully hydration process with higher fine content.

Rao (2001) has developed a general formula which related the strength to water-to-cement ratio of varied mortar proportions of 1:2, 1:2.5, and 1:3, while, Singh et al. (2015) has encountered water – to- cement ratio of the mortar proportions of 1:3, 1:4, 1:5, 1:6 and 1:7. The former established a general formula that would be applicable when using Portland Pozzolanna cement, PCC (blended cement with pozzolanic materials such as fly ash, calcium clay…etc.). In this paper, a more general expression for all four mortar mixes i.e. 1:3, 1:4, 1:5, and 1:6 are evaluated. The experimental results of compressive strength of cube specimens with water-to- binder ratio of all the four mortars at the age of 28-days are shown in **Figure 4**.

Generalized correlation expression for all the four mortar mixes is evaluated using regression analysis as function of water-to-binder ratio is shown in **Figure 5**. Generally, the relationship between the 28 days compressive strength of concrete and water – to - binder is translated to the following formula:-

$$\sigma_c = n_1 (w/b)^{n_2} \quad (7)$$

Where parameters n_1, and n_2 are assessed and reported, as shown in **Table 5**.

From above mentioned results, the practitioners can use the above equations in designing the strength of any mortar for any purpose, accordingly. **Table 4** reported the compressive strength of concrete for both cylinder and cube specimens. The Table, also, depict the predicted values of compressive strength of concrete using **Equation 7** versus the experimental one.

In addition to, the C.O.V. % (coefficient of variation) for each three samples according to the corresponding water-to- binder ratio and cement:sand ratios were recorded, respectively. The minimum and the maximum C.O.V. % assessed by values of 1.26 and 6.79 %. Finally the difference between the experimental results and those predicated by equations are approximately ± 8%.

As the Abram's Law was introduced and evaluated through the regression analysis, also Bolomey's Equation was presented. Bolomey's equation is relating the cement-to-binder ratio to the compressive strength of concrete by two constants A, and B. These two constants depends mainly on the material properties of the mortar ingredients used. In this paper, the constants A, and B are evaluated for the four mixes (1:3, 1:4, 1:5, and 1:6) of cube specimens. The equation was on the following form:-

$$\sigma_c = \frac{A}{(w/b)} + B \quad (8)$$

It should be mentioned that the constants A, and B are assessed using the curve fitting tool in Mat LAB software, then after, reported as shown in **Table 5**.

Split Tensile strength

48 cylinders of 100 mm in diameter and 200 mm in height were cast and tested in split tensile strength. As clear from **Figure 6**, the cylinder subjected to split tensile forces and split into two pieces. **Figure 7** represented the splitting into two pieces clearly as failure pattern. The results of the split tensile strength for cylinder of the cement mortar is presented on **Table 6**. From the **Table 6**, it is deduced that the results is compatible with the compressive strength of the cylinders as clear in **Table 4** and **6**. The relationship between the water -to- binder ratio and the split tensile strength is drawn, as shown in **Figure 8**.

The results show the highest tensile strength value at cement-to-sand ratio of 1:3 with a value of 2.45 MPa at water – to – binder ratio of 0.5. On other hand, the highest tensile strength in each mix was at 0.7 water-to-binder ratios for the three mixes (1:4, 1:5 and 1:6). It is obvious as the water-to- binder ratio increases the compressive strength and the split tensile strength decrease in case of mortar portion of 1:3, however, this relationship was altered when using the other portion of mix mortar 1:4, 1:5 and 1:6. This could be attributed to the addition of silica fume which requires more water to be workable and fully achieve the hydration process of cement. The results were, then; used to assess the Abram's law parameters and deduced the empirical expression as shown in **Table 5**.

This empirical expression was used to predict the relationship between the split tensile strength of the cylinders specimen of the cement mortar for various cement – to- sand ratios at 28 days age. The expression was clarified as following:-

$$f_{ct} = n_3 (w/b)^{n_4} \quad (9)$$

Where parameters n_3 and n_4 are assessed as in **Table 5** for the four mortar mixes.

Similarly to the compressive strengths of mortar, Bolomey's equation was implemented to generate an expression for split tensile strength of cylinder specimens. Parameters C and D were evaluated using the curve fitting tool in Mat Lab software for the four mortar mixes.

Thus, the practitioner can estimate the design strength of mortar required for the specific purpose through using the expressed relationship between the split tensile strength and water –to- binder ratio. Accordingly, the form of the **Equation 10** which relates the tensile strength with water –to- binder ratio was as seen below:

$$f_{ct} = \frac{C}{(w/b)} + D \quad (10)$$

Figure 9 shows the relationship between the predicted split tensile strength of cement mortar and water –to- binder ratio. **Table 6** reported the tensile strength of concrete for split cylinder specimens. The Table, also, depict the predict values of splitting tensile strength of concrete using **Equation 9** and the difference from the experimental one.

Additionally, the C.O.V % for each of the three samples according to the corresponding water – to – binder ratio and cement – to – sand ratios, respectively were recorded.

The minimum and maximum C.O.V % are assessed by values of 1.54% and 11.58%. Finally, the difference between the experimental results and those predicted by **Equation 9** is approximately between ± 6%.

Compressive strength and the corresponding tensile strength

As clear, that the tensile strength specimens only accounted for the mixes (cement: sand ratios) at all the water -to- binder ratios except 0.4. Thus, for each mix and water -to- binder ratio, there is a value for compressive strength and a corresponding tensile strength. Accordingly, a relationship between the compressive and tensile strength was concluded through these results, as shown in **Figure 10**. **Figure 10** represents the compressive strength against the tensile strength for each mix and water -to- binder ratio. The equations deduced, as shown from **Figure 10,** was in the form of power model.

It should be deduced that as the compressive strength increases the tensile strength, generally, increases. Correspondingly, a nonlinear **Equation 11** was generated to relate the tensile strength as function of compressive strength of mortar, as shown below:

$$f_{ct} = 0.1507 * \sigma_c^{0.9843} \quad (11)$$

V. CONCLUSIONS

Contradicting to Singh et al. 2015 and other researchers (Rao 2001, Yeh 2006), the compressive strength of cement mortar increased when cement replaced by 15% of silica fume at high cement – to – sand till it reach water – to – binder ratio of a value 0.7. The influence of water- to – binder ratio using 15% of silica fume and cement- to – sand proportions on both compressive and split tensile strengths of mortar were studied and investigated. Moreover, an empirical equations deduced to easily predict the strength using only water-to-binder ratio. An expression for optimum water content required for workable mortar and better flow ability was introduced and assessed. The decrease in cement content requires water for making mortar workable and achieves the fully hydrated developed strength. Abram's law seems to be applicable with small shift towards increasing water – to –binder ratio for high strengths at higher fine aggregate content. Empirical equation as well as assessing the constants for Bolomey's equation were developed and generated for both compressive and split tensile strength. These equations can be helpful in predicting the compressive and split tensile strength when designing cement mortar mix for masonry structures.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the support of the Civil Engineering Program at German University in Cairo, GUC as well as the material laboratory of Civil Engineering Program and the technician Ali Mohammed for his faithful and supportive environment that he provided.

REFERENCES

[1]. Duff, Design of Concrete Mixtures Bulletin No. 1, Structural Materials Laboratory, Lewis Institute, Chicago, 1918, p. 20.

[2]. Ganaw, A. Ashour, Rheological properties of mortars prepared with different sands, ACI Mater. J. 111.5 (2014) 561–568.

[3]. ASTM C39 / C39M-18, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2018, www.astm.org

[4]. ASTM C496 / C496M-17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2017, www.astm.org.

[5]. Atsushi YATAGAI, Nobukazu NITO, Kiyoshi KOIBUCHI, Shingo MIYAZAWA, Takashi YOKOMURO and Etsuo SAKAI, "Properties of Concrete with Blast-Furnace Slag Cement Made from Clinker with Adjusted Mineral Composition", Third International Conference on Sustainable Construction and Technologies, 2010 http://www.claisse. Info/ Procedings.htm.

[6]. BS EN 12390-3 (2009) Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. Management Centre, Brussels.

[7]. Bühler , Eckart R. Two Decades of Ready-Mixed High Performance Silica Fume Concrete. Norchem, Inc. Accessed May 5, 2017. http://www.norchem.com/pdf/technical-papers-articles-two-decades.pdf.

[8]. F.A. Oluokun, Fly ash concrete mix design and water–cement ratio law, ACI Materials Journal 91 (4) (1994) 362–371.

[9]. G.A. Rao, Generalization of Abrams' law for cement mortars, Cem. Concr. Res. 31 (2001) 495–502.

[10]. Gee, Michael S., Weston T. Hester, and Robert Prisby. "Guide to Using Silica Fume in Precast/Prestressed Concrete Products." PCI Journal, Sept. & Oct. 1994, 36-45.

[11]. Holland, T.C., Krysa, A., Luther, M., and Liu, T., 1986,"Use of silica fume concrete to repair abrasion erosion damage in the kinzua dam stilling basin," proceedings, CANMET/ACI second international conference of fly ash, silica fume, slag, and natural pozzlans in concrete, Madrid, SP-91, Vol.2, American concrete Institute, Detroit, pp. 841-864.

[12]. Holland, Terence C. Silica Fume User's Manual. Technical paper no. FHWA-IF-05-016. Silica Fume Association. Springfield: Federal Highway Administration, 2005. 0-194.

[13]. Hooton, R. D. (1993) " Influence of silica fume replacement of cement on physical properties and resistance of sulfate attack, freezing and thawing, and alkalisilica reactivity" ,ACI Materials Journal, Vol. 90, No. 2, pp. 143-151.

[14]. Hunchate, Sudarsana R., Sashidhar Chandupalle, Vaishali G. Ghorpode, and Venkata R. T.C. "Mix Design of High Performance Concrete Using Silica Fume and Superplasticizer." International Journal of Innovative Research in Science, Engineering and Technology 3, no. 3 (March 2014): 10736-0742.

[15]. Yeh, Generalization of strength versus water–cementitious ratio relationship to age, Cem. Concr. Res. 36.10 (2006) 1865–1873.

[16]. K.G. Babu, G.S.N. Rao, Efficiency of fly ash in concrete with age, Cement and Concrete Research 26 (3) (1996) 465–474.

[17]. Kamran Muzaffar Khan & Usman Ghani, "EFFECT OF BLENDING OF PORTLAND CEMENT WITH GROUND GRANULATED BLAST FURNACE SLAG ON THE PROPERTIES OF CONCRETE", 29th Conference on OUR WORLD IN CONCRETE & STRUCTURES: 25-26 August 2004, Singapore.

[18]. L.K.A. Sear, J. Dews, B. Kite, F.C. Harris, J.F. Troy, Abrams law, air and high water-to-cement ratios, Constr. Build. Mater. 10.3 (1996) 221–226.

[19]. MATLAB and Statistics Toolbox Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States.

[20]. Metwally abd allah Abd elaty, "Compressive strength prediction of Portland cement concrete with age using a new model", HBRC Journal (2014) 10, 145–155.

[21]. N.H. Thanh, Optimal concrete composition based on paste content for ferrocement, J. Ferrocem. 21.4 (1991) 331–350.

[22]. N.P. Rajamane, P.S. Ambily, Modified Bolomey equation for strengths of lightweight concretes containing fly ash aggregates, Mag. Concr. Res. 64. 4 (2012) 285–293.

[23]. S. Pavía and E. Condren, " A study of the durability of OPC vs. GGBS concrete on exposure to silage effluent", Journal of Materials in Civil Engineering, Vol.20, No. 4, 313-320, 2008. S. Wild, B.B. Sabir, J.M. Khatib, Factors influencing strength development of concrete containing silica fume, Cement and Concrete Research 25 (7) (1995) 1567–1580.

[24]. S. Wild, B.B. Sabir, J.M. Khatib, Factors influencing strength development of concrete containing silica fume, Cement and Concrete Research 25 (7) (1995) 1567–1580.

[25]. S.B. Singh n, Pankaj Munjal, Nikesh Thammishetti, "Role of water/cement ratio on strength development of cement mortar", Journal of Building Engineering, 4 (2015) 94–100

[26]. S.-H. Han, J.-K. Kim, Effect of temperature and age on the relationship between dynamic and static elastic modulus of concrete, Cement and concrete research 34 (7) (2004) 1219–1227.

[27]. S.J. Barnett, M.N. Soutsos, S.G. Millard, J.H. Bungey, "Strength development of mortars containing ground granulated blast-furnace slag: Effect of curing temperature and determination of apparent activation energies", Cement and Concrete Research 36 (2006) 434 – 440.

[28]. Sasan Parniani,, Mohd.Warid Hussin and Farnoud Rahimi Mansour "Compressive strength of high volume slag cement concrete in high temperature curing", Advanced Materials Research Vols. 287-290, 2011, pp 793-796.

[29]. Sharp, James W. Silica modified cement. US Patent 558,463, filed October 12, 1944, and issued November 12, 1946.

[30]. T. Vijaya Gowri, P. Sravana, and P. Srinivasa Rao "On the Relationship between Compressive Strength and Water Binder Ratio of High Volumes of Slag Concrete", International Journal of Applied Engineering Research, Research India Publications, Volume 11, Number 2 (2016) pp 1436-1442

[31]. Thomas, M.D.A., Shehata, M.H., Shashiprakash, S.G., Hopkins, D.S. and Cail, K. "Use of ternary cementitious systems containing silica fume and fly ash in concrete." Cement and Concrete Research, Vol. 29 (8), 1999, pp. 1207-1214.

[32]. S. Tamilarasan and P. Perumal, "Performance Study of Concrete using Ggbs as a Partial Replacement Material for Cement", European Journal of Scientific Research, ISSN 1450-216X Vol. 88 No 1 October, 2012, pp.155-163, © EuroJournals Publishing, Inc. 2012 http://www.europeanjournalofscientificresearch.com.

[33]. Whiting, D., and Detwiler, R., 1988, "Silica-Fume Concrete for Bridge Decks," Report 410, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 107 pp.

[34]. Yogendran, Y., Langan, B. W., HaqueM. N. and Ward, M. A., Silioca Fume in High Strength Concrete, ACI Materials Journal, 84(2), 124-129 (1987).

Table 1. Physical properties of Portland Ordinary Cement **(OPC)**

OPC properties	**Test results***
Blaine Fineness, (m^2/Kg)	320
Specific gravity	3.15
Initial and Final setting time (min)	150 and 360
Soundness: Le Chatelier test, mm) maximum	1

* Egyptian Specifications (4756 – 1 /2009)

Table 2. Chemical properties of Portland Ordinary Cement **(OPC)**

OPC properties	**Test results***
Magnesium Oxide (MgO)	1.4
Sulphur Trioxide (SO_3)	2.755
Loss of Ignition (LOI)	2.5%
Insoluble residue	0.55%
Chlorides content	0.03
Clinker Content	
Tri-Calcium Silicate (C_3S)	52.5%
Di-Calcium Silicate (C_2S)	22.5%
Tri-Calcium Aluminate (C_3A)	6.5%
Tetra-Calcium Alumino ferrite (C_4AF)	12%
Lime Saturation Factor	0.93

* Egyptian specifications (4756 – 1/ 2007)

Table 3. Physical and chemical properties of Silica Fume* and fine aggregate (Sand)

Definition	Symbol
Silica fume	
Particle size (typical)	< 1μm (0.5 μm)
Bulk density	425 Kg / m^3
Specific Gravity	2.2
Specific surface	22500 m^2/Kg
SiO_2	91%
CaO	< 1%
Fine aggregate (Sand)	
Specific Gravity	1.7
Materials finer than 75μm (sieve No.200)	2%

* As specified by the SIKA © FHWA-IF-05-016, Silica Fume Association Manual, April, (2005)

Table 4. Compressive strengths of cube and cylinder specimens from experimental and analytical predicted

Cement : Sand	w/c	Cube compressive strength $\sigma_{c28, exp}$ (MPa)	% COV	28 Days Compressive Strength Predicted from **Equation 7;** $\sigma_{c28, Pred.}$ (MPa)	% Difference	Cylinder compressive strength $\sigma_{c28, exp}$ (MPa)	% COV
Ratio 1:3	0.4	25.5	4.54	27.6	8.2	23.0	6.47%
	0.5	24.6	3.73	22.7	-7.6	19.9	5.31%
	0.6	20.4	6.79	19.3	-5.5	16.8	9.67%
	0.7	17.0	3.98	16.9	-0.7	14.1	5.68%
	0.8	14.1	4.23	15.0	6.7	11.8	6.02%
Ratio 1:4	0.4	14.9	3.62	15.1	1.7	12.6	5.16%
	0.5	16.3	2.21	16.2	-0.4	14.0	3.15%
	0.6	17.6	1.32	17.2	-2.1	15.3	1.89%
	0.7	18.6	1.26	18.1	-2.7	16.3	1.80%
	0.8	18.2	4.10	18.9	3.6	16.2	5.85%
Ratio 1:5	0.4	7.6	2.83	8.0	5.1	6.8	4.03%
	0.5	9.8	5.10	9.5	-3.0	7.9	7.27%
	0.6	11.4	4.32	10.9	-4.4	9.3	6.16%
	0.7	12.9	2.92	12.3	-5.2	10.7	4.17%
	0.8	12.6	3.81	13.6	8.2	10.5	5.43%
Ratio 1:6	0.4	7.2	2.63	7.4	3.8	6.1	3.74%
	0.5	8.6	3.62	8.4	-2.5	7.4	5.16%
	0.6	9.5	1.85	9.3	-2.5	8.3	2.64%
	0.7	10.6	3.21	10.1	-5.0	9.3	4.57%
	0.8	10.2	1.54	10.9	6.6	9.1	2.20%

Table 5. Values of strength parameters

Cement : sand	n_1	n_2	regression coefficient	A	B	regression coefficient	n_3	n_4	regression coefficient	C	D	regression coefficient
1:3	12.31	-0.88	0.92	9.28	3.91	0.89	1.32	-1.18	0.99	1.66	-0.35	1.00
1:4	20.26	0.32	0.92	-2.98	22.38	0.95	2.38	0.26	0.82	-0.34	2.67	0.86
1:5	16.12	0.77	0.92	-4.35	18.56	0.97	2.10	0.58	0.86	-0.59	2.57	0.90
1:6	12.26	0.55	0.91	-2.67	13.95	0.95	1.70	0.96	0.96	-0.65	2.15	0.98

Table 6. Spilt tensile strengths of cylinder specimens from experimental and analytical predicted

Cement : Sand	w/c	cylinder split tensile strength $f_{ct28, exp}$ (MPa)	% COV	28 Days Tensile Strength Predicted from **Equation 9**; $f_{ct28, Pred}$ (MPa)	% Difference
Ratio 1:3	0.5	2.94	7.15%	2.98	1.33
	0.6	2.44	2.27%	2.41	-1.45
	0.7	2.04	11.58%	2.01	-1.62
	0.8	1.69	11.09%	1.72	1.73
Ratio 1:4	0.5	1.96	10.41%	1.99	1.56
	0.6	2.11	7.63%	2.08	-1.21
	0.7	2.23	9.50%	2.17	-2.79
	0.8	2.19	11.13%	2.24	2.53
Ratio 1:5	0.5	1.36	2.75%	1.404	2.91
	0.6	1.59	3.18%	1.561	-2.01
	0.7	1.81	4.47%	1.707	-5.58
	0.8	1.76	8.15%	1.845	5.02
Ratio 1:6	0.50	0.86	3.62%	0.88	1.69
	0.60	1.05	1.85%	1.04	-0.32
	0.70	1.27	3.21%	1.21	-5.05
	0.80	1.32	1.54%	1.38	3.91

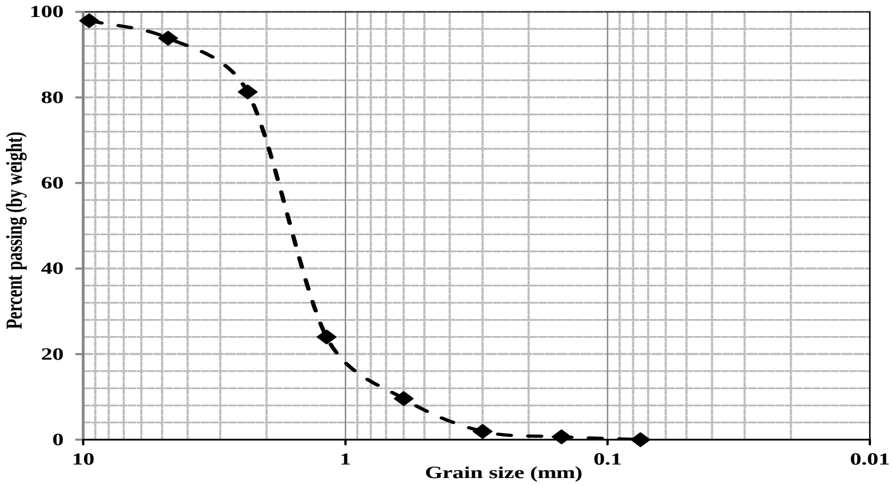

Fig. 1. A schematic diagram presenting the particle size distribution curve of sand

Fig. 2. Typical cube specimen failure mode under compressive testing of the cube

Fig. 3. Typical specimen cylinder inside the compression testing machine

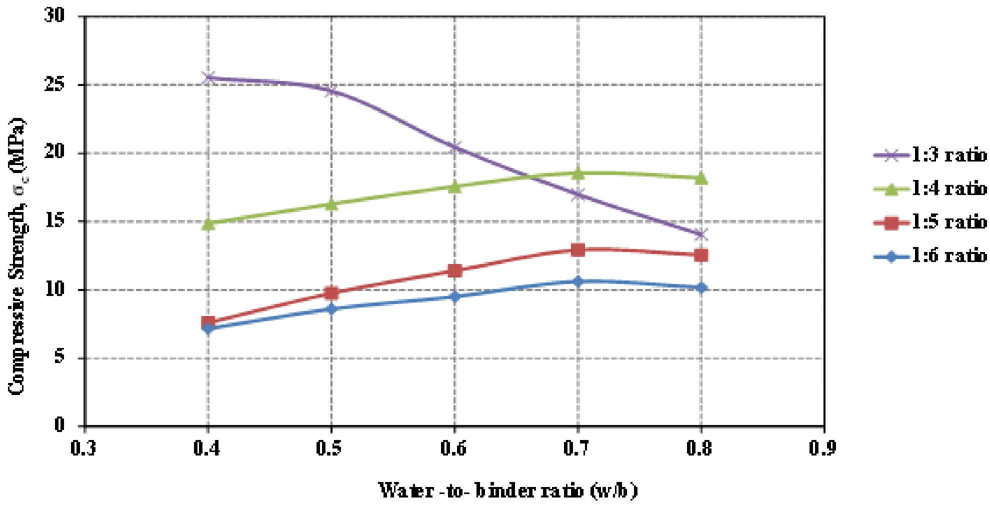

Fig. 4. Relationship between experimental compressive strength of cement mortar and water –to- binder ratio

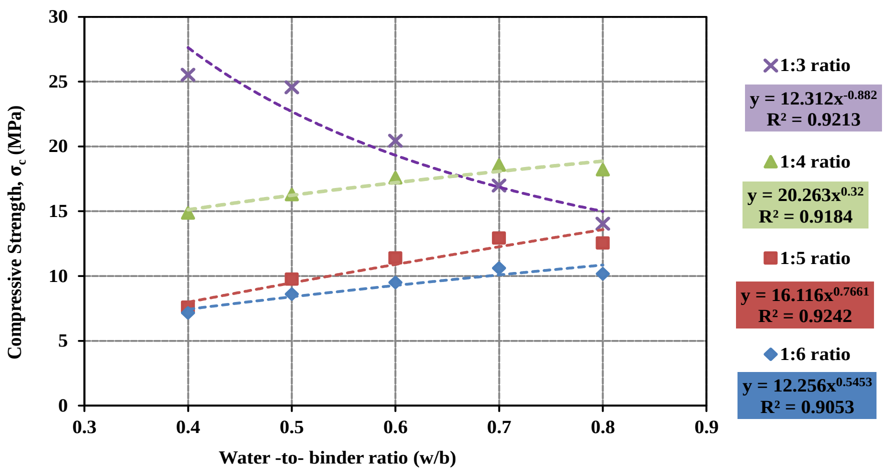

Fig. 5. Relationship between predicted compressive strength of cement mortar and water –to- binder ratio

Fig. 6. Split tensile strength of cylinder specimen.

Fig. 7. Failure pattern of cylinder under splitting tensile strength (Indirect)

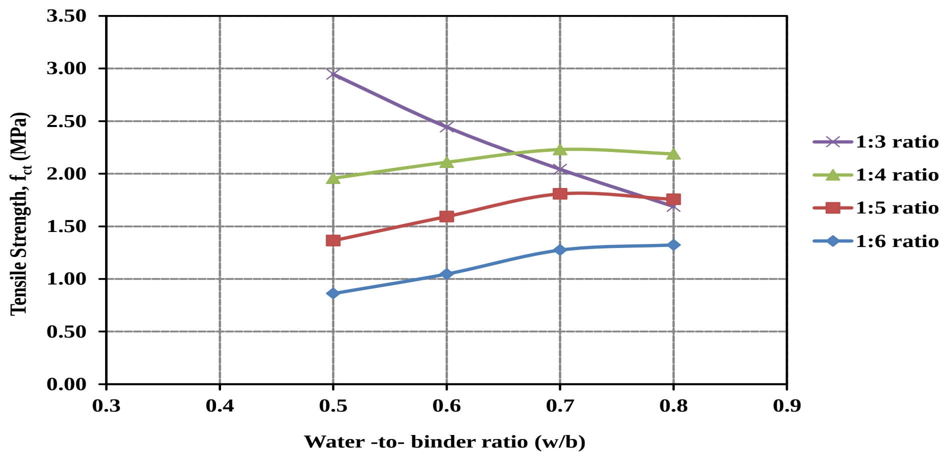

Fig. 8. Relationship between experimental split tensile strength of cement mortar and water –to- binder ratio

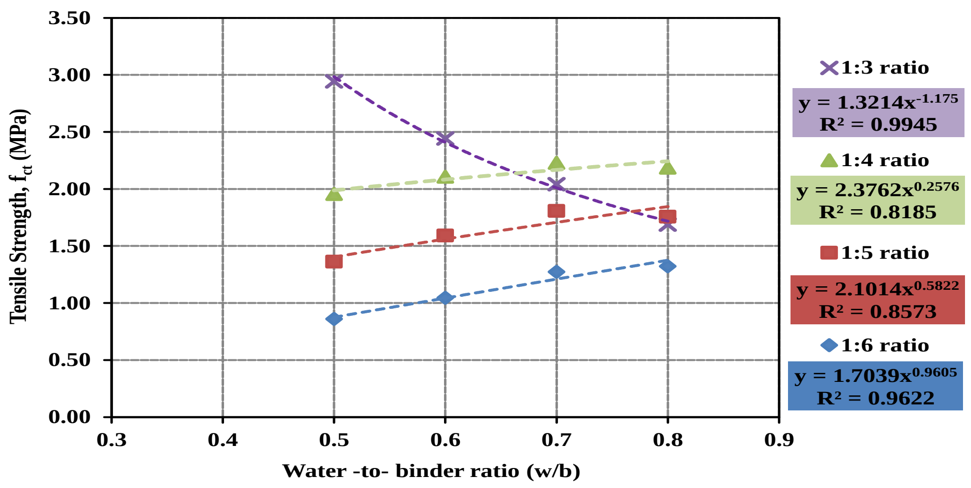

Fig. 9. Relationship between Predicted split tensile strength of cement mortar and water –to- binder ratio

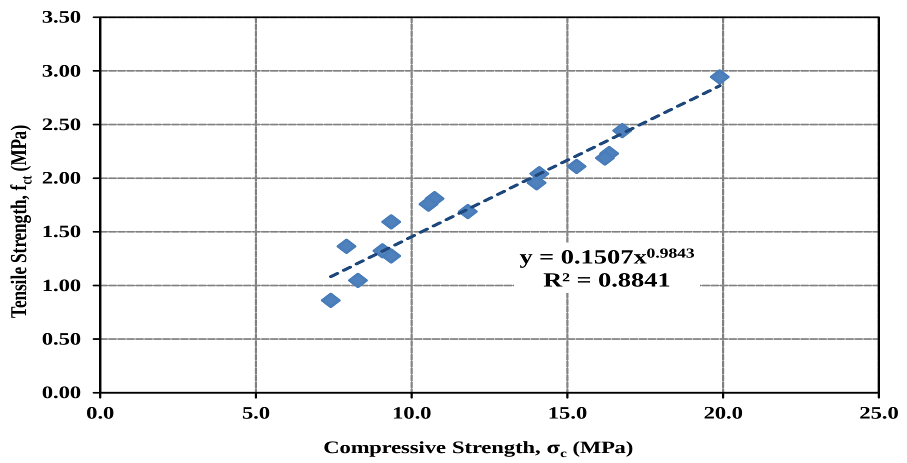

Fig. 10. Relationship between split tensile and compressive strength of cement mortar