A QUANTITATIVE EVALUATION OF BOND STRENGTH BETWEEN COARSE AGGREGATE AND CEMENT MORTAR IN CONCRETE

Tareq S. Al-Attar, PhD

Assistant Professor of Civil Engineering, Building and Construction Engineering Department, University of Technology, Iraq

Abstract

The hardened concrete could be considered as a three-phase composite material consisting of cement paste, aggregate and interface zone between them. The bond between cement paste and aggregate depends largely on the interface zone characteristics. Most methods and specimens used to measure bond strength between aggregate and cement paste are not standardized and could be only described as a gross simplification of the real situation around interfaces. The present work represents a proposed quantitative evaluation for the bond strength that depends mainly on the results of the uniaxial compression test of concrete which is a simple and standardized test. The used coarse aggregate was intentionally treated with engine oil and with oil paint to investigate the effect of these coatings on bond strength. The effectiveness of surface coating by engine oil or paint was tested through the comparison of water absorption for coarse aggregate before and after the treatment. Both methods were highly successful in preventing water ingress inside aggregate particles. The experimental program included absorption for coarse aggregate, and slump, compressive strength, and splitting tensile strength tests for concrete. The program for strength tests was extended to the age of 180 days.

The results of the present work showed that the estimated bond strength at any time ranged from (6.1 - 8.4) percent of the compressive strength for the investigated concrete. It was concluded that the values of bond to splitting tensile strength ratio could be considered as an indication to weather the failure of concrete is occurred due to bond lose or because the stresses at the interface zone had exceeded the tensile strength.

Keywords: Absorption, bond strength, engine oil, interface-zone, oil paint, splitting tension, uniaxial compression

Introduction

The hardened concrete could be considered as a three-phase composite material consisting of cement paste, aggregate and interface between cement paste and aggregate. The load transfer mechanism between these phases depends on the type of cement paste, surface characteristics of aggregate and adhesive bond developed at the interface[20].

The bond between cement paste and aggregate depends largely on the interface zone characteristics. The cement-aggregate bond results from some combination of mechanical interlocking of cement hydration products with the aggregate surface and chemical reaction between aggregate and cement paste[21].

The interface zone is believed to play a major role in the cracking of concrete. Its stiffness and strength are decisive in governing whether a crack should grow around an aggregate particle, or rather, would follow a path through the grain. The relative values of the bond strength and stiffness with respect to the matrix and/or aggregate strength and stiffness are of major importance, rather than the absolute values of all these parameters[22]. Different test methods and specimens had normally used for measuring the tensile or shear bond strength between aggregate and cement paste or mortar, as shown in Figs. 1 and 2. Van Mier and Vervuurt[23] described the situation in all these tests as a gross simplification of the real situation around interfaces and they seemed the most practical manner of getting some insight in the matter.

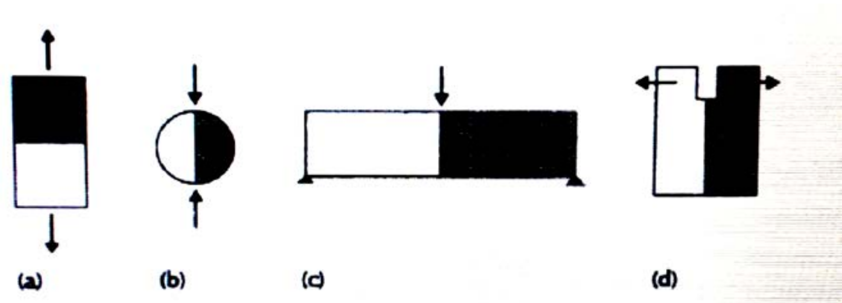

Fig. 1: Different composite test geometries for measuring the tensile or flexural bond strength between aggregate and cement matrix: (a) uniaxial tension test, (b) splitting tensile test, (c) three point bend test, and (d) wedge splitting test[24].

[20] Appa Rao, G., and Raghu Prasad, B. K. "Influence of Interface Properties on Fracture Behavior of Concrete" Sadhana (Indian Academy of Sciences), V. 36, Part 2, 2011, pp. 193-208.
[21] Struble, L., Skalny, J., and Mindess, S. "A Review of the Cement- Aggregate Bond" Cement and Concrete Research, V. 10, 1980, pp. 277-286.
[22] Van Mier, J. G. M., and Vervuurt, A. " Engineering and Transport Properties of the Interface Transition Zone in Cementitious Composites –

Test Methods and Modelling for Determining the Mechnical Properties of the ITZ in Concrete" RILEM Publications, Report No. 20, 1999, pp. 19-52.
[23] ibid
[24] ibid

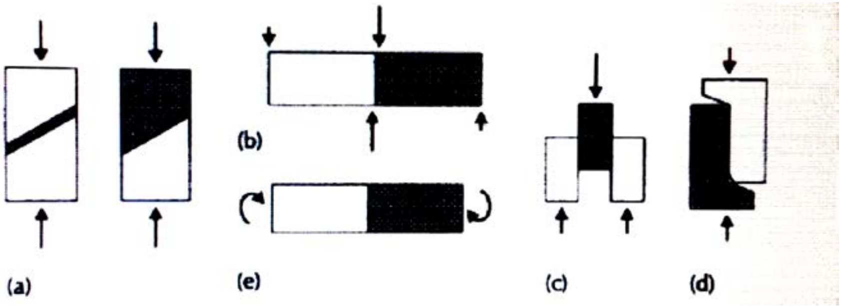

Fig. 2: Different composite test geometries for determining of the shear strength of the ITZ: (a) slant shear test, (b) four-point-shear beam, (c) push-through cube, (d) compact shear specimen, and (e) cylinder subjected to torsion [3].

The effect of the transition zone on the mechanical and transport properties of concrete is obscure. This is largely due to the difficulty in measuring the properties of real transition zones, as opposed to the artificial ones usually created for testing by casting paste against rock surfaces. However, there are strong indications that this zone does influence concrete properties such as strength, stiffness, and permeability[25].

Hardened concrete, as a heterogeneous material, contains different types of discontinuities: *i.e.* voids, pores, and microcracks. According to brittle fracture theory that was first presented by Griffith, failure is initiated by the largest crack which is oriented in the direction normal to the applied load. Griffith's hypothesis applies to failure under the action of a tensile force but it can be extended to fracture under bi- and triaxial stress and also under uniaxial compression[26].

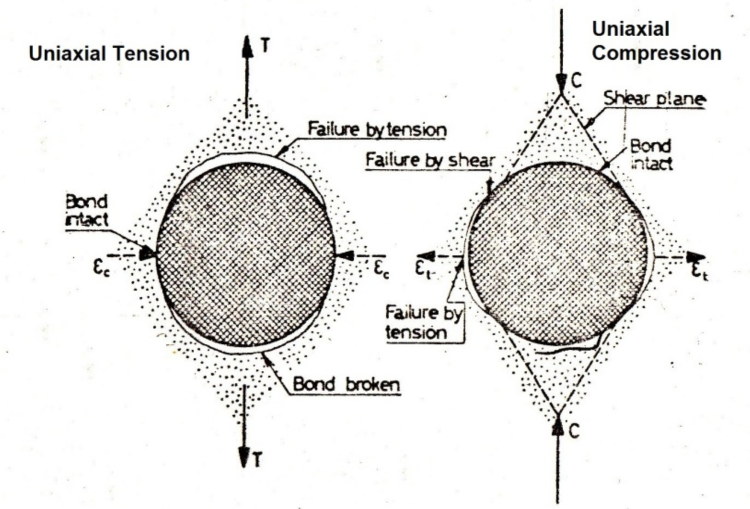

Fig. 3: Stress and strain state around a grain of aggregate[27].

[25] Alexander, M. G., Mindess, S., Diamond, S., and Qu, L. "Properties of Paste-rock Interfaces and Their Influence on Composite Behaviour" Materials and Structures, V.28, 1995, pp. 497-506.
[26] Neville, A. M., *Properties of Concrete*, 4th ed., Pearson Education Limited, UK, 2004, 844 pp.
[27] Avram, C., Facaoaru, I., Filimon, I., Mirsu, O., and Tertea, I., *Concrete Strength and Strains*, Elsevier, New York, 1981, 558 pp

Under uniaxial compressive states of stress[28] [29] evidence suggests that, first, stable cracks are initiated in the mortar matrix parallel to the direction of applied compression. As the load is increased, the cracks multiply and extend in this same direction until, in the vicinity of mineral aggregate inclusions, the fracture path divides and travels around, rather than through, the hard particles, Fig. 3.

After final disruption and failure of a specimen, this fracture mechanism produces isolated particles of aggregate adhering to which are small ‘cones’ of mortar at each end aligned in the direction of maximum principal compressive stress, as shown in Fig. 4[30].

Fig. 4: Aggregate particles after failure in uniaxial compression[31].

Research Significance

Measuring the real properties of transition zone is so difficult; therefore, a proposed evaluation for the bond strength is investigated. This evaluation depends mainly on the results of the uniaxial compression test of concrete which is a simple and standardized test. It was also aimed to investigate the effects of engine oil and oil paint as aggregate coatings on bond, which could act as barriers and reduce or diminish the bond between aggregate and cement paste.

[28] ibid
[29] Newman, J., and Choo, B. S., *Advanced Concrete Technology - Concrete Properties*, Elsevier, UK, 2003, 314 pp.
[30] ibid
[31] ibid

Experimental Work

Materials

Ordinary Portland cement was used throughout the experimental part of this research. It was conforming to the American standard (ASTM C150-05, Type I)[32]. The fine aggregate was natural sand with fineness modulus of 2.7, sulfate content of 0.27 percent, and water absorption of 1.05 percent. It was within the gradation limits of the American standard (ASTM C33-03)[33]. Two types of gravel, natural and crushed, were used as coarse aggregate. The maximum size for both types was 19 mm. The dry rodded unit weights were 1680 and 1600 kg/m^3 for natural and crushed gravel respectively. The sulfate content was 0.08 percent for natural gravel and 0.056 percent for crushed gravel. The water absorption values were 0.83 and 0.96 percent for natural and crushed gravel respectively. Both types of gravel were conforming to the American standard (ASTM C33-03).

Table 1: Properties of used Portland cement

No.	Property		Test Result
1	Compound Composition (Bouge's Equations), %.	C_3S	42.8
		C_2S	28.2
		C_3A	4.8
		C_4AF	15.2
2	Specific Surface (Blaine), m^2/kg.		310
3	Soundness (Autoclave), %.		0.18
4	Setting Time, min.	Initial	140
		Final	350
5	Compressive Strength at, MPa:	3 days	18
		7 days	25
		28 days	32

Treatment of Coarse Aggregate

To achieve the goals of the experimental program, the used coarse aggregate had to be prepared. In the beginning, all the coarse aggregate was washed to remove the dust and fine materials and to assure clean surfaces. After that the aggregate was air-dried inside the laboratory.

Each type of coarse aggregate was separated in three batches. The first was kept in plastic containers in its natural conditions. The second batch was soaked in engine oil for different periods (12, 24, 48, and 96 hours). It was found that soaking the aggregate in oil for more than 48 hours does not make a significant change in weight. Therefore, a soaking period of 48 hours was adopted throughout the program. According to the gained experience in this

[32] American Society for Testing and Materials, "Standard Specification for Portland Cement, ASTM C 150 – 05" Annual Book of ASTM Standards, 2006, 0402, USA, 8 pp.

[33] American Society for Testing and Materials, "Standard Specification for Concrete Aggregates, ASTM C 33 – 03" Annual Book of ASTM Standards, 2006, 0402, USA, 11 pp.

work, storing the aggregate for more than 10 hours after soaking would cause the loss of the thin oil film from external surfaces of aggregate.

For the third batch, the aggregate was painted with oil paints. The aggregate was soaked in a paint container and then allowed to dry (for at most 24 hours) on a wire mesh which gave the chance to the excess paint to be drained. In this case there was always a check that all the surfaces of each particle had been covered with a layer of paint. Painted aggregate was stored on polyethylene sheets in the laboratory and treated with care during batching and mixing.

Effectiveness of Surface Coating for Coarse Aggregate

The surface coating by engine oil film or paint was tested through calculating the absorption of aggregate after oil-soaking or painting. Hypothetically, soaking the aggregate in oil for the designated period will make all the available pores to be filled with oil so there will be no space for water to penetrate inside the aggregate particles. For painting, it is assumed that the paint will make a barrier on the surface of particles which will prevent the ingress of water.

To test these hypotheses, four samples of coarse aggregate (two of each type) were first oven-dried (110 ± 5 ^{O}C for 24 hours.). Then, two of them were oil-soaked for 48 hours and the others were painted in the aforementioned procedure. The four samples were weighted to the nearest 0.1 g, W_1. After that they were immersed in water at room temperature for 24 hours and the surface moisture removed with cloth towel and the weight of each sample was measured to the nearest 0.1 g, W_2. The absorption was measured for each sample and compared to the original values (without oil-soaking or painting).

Mixes

Two water to cement ratios, 0.4 and 0.5 by weight, were selected to produce four reference mixes with different strength levels. The slump for these mixes was chosen to be 50 ± 25 mm. The mix proportioning was done according to the ACI Committee 211 standard practice[34]. Trial mixes were made to ensure the desired workability and the calculated proportions were adjusted. Table 2 shows the final proportions for the four reference mixes. The same mix proportions were adopted to produce four mixes with oil-soaked coarse aggregate and another four mixes for painted aggregate. Therefore, the overall number of mixes was twelve. Letters O (for oil-soaking) and P (for painting) were added to the mix notation to differentiate between different mixes. For example, mix M3P means a concrete

[34] ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete - ACI 211.1-91 (Reapproved 2002)" ACI Manual of Concrete Practice, USA, 2004, 38 pp.

mix made by using painted crushed gravel with water to cement ratio of 0.5 by weight of cement

Table 2: Details of investigated concrete mixes

Materials, kg/m^3	Mix M1	Mix M2	Mix M3	Mix M4
	W/C = 0.4 by weight		W/C = 0.5 by weight	
	Crushed Gravel	Uncrushed Gravel	Crushed Gravel	Uncrushed Gravel
Water	190	180	190	180
Cement	475	450	380	360
Coarse Aggregate	1008	1058	1008	1058
Fine Aggregate	672	657	767	747

Testing Program

The testing program included the following tests and according to the mentioned standard methods:

1. Absorption of coarse aggregate (ASTM C 127 - 04)[35].
2. Slump test of fresh concrete (ASTM C 143/ C143M - 05a)[36].
3. Compressive strength of concrete cylinders (ASTM C 39/ C39M - 05)[37].
4. Splitting tensile strength of concrete cylinders (ASTM C 496/ C496M - 04)[38].

The program had been extended to the age of 180 days for hardened concrete tests. Cylindrical concrete specimens, with dimensions of d= 100, h= 200 mm, were tested for compressive and splitting tensile strength tests. Gypsum plaster was used as a capping material for the tested cylinders. All concrete specimens were water-curied until the age of test (7, 28, 60, 90, and 180 days).

Results And Discussion

Effect of Surface Coatings on Aggregate Absorption

Table 3 shows the results of absorption test (ASTM C 127 - 04)[39] carried out on the original coarse aggregate and after oil-soaking and painting. According to these results, there was a significant reduction in absorption values due to applying of coatings. For crushed

[35] American Society for Testing and Materials, “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate, ASTM C 127 – 04” Annual Book of ASTM Standards, 2006, 0402, USA, 6 pp.
[36] American Society for Testing and Materials, “Standard Test Method for Slump of Hydraulic-Cement Concrete, ASTM C 143/C 143M – 05a” Annual Book of ASTM Standards, 2006, 0402, USA, 4 pp.
[37] American Society for Testing and Materials, ” Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM C 39/C 39M – 05” Annual Book of ASTM Standards, 2006, 0402, USA, 7 pp.
[38] American Society for Testing and Materials, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM C 496/C 496M – 04” Annual Book of ASTM Standards, 2006, 0402, USA, 5 pp.
[39] American Society for Testing and Materials, “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate, ASTM C 127 – 04” Annual Book of ASTM Standards, 2006, 0402, USA, 6 pp.

aggregate, oil-soaking caused 93.7 percent reduction in absorption, meanwhile, painting resulted in 99.7 percent reduction. The corresponding values for uncrushed aggregate were 95.4 and 99.5 percent for oil-soaking and painting respectively. Natural coatings (clay and micro-fines) had been often reported to increase water demand for aggregate[40]. But the present used coatings have acted as barriers that prevent the water ingress into the aggregate particles or to be adsorbed on their surfaces.

Xie and Beaudoin[41] stated that the thickness of the water layer on the aggregate surface at the beginning of the mixing has a negative effect on bond strength at the interface between nonporous aggregate and Portland cement paste.

Table 3: Absorption results

Type of Absorption	**Type of Aggregate**	
	Crushed	**Uncrushed**
Original Absorption, %.	0.96	0.83
Absorption after Oil-soaking, %.	0.02	0.006
Absorption after Painting, %.	0.001	0.0007

Effect of Surface Coatings on Slump of Concrete

As mentioned earlier, slump for the prepared reference mixes was chosen to be 50 ± 25 mm. It was intended to choose low workability concrete to investigate the effect of variation in aggregate absorption on final workability of the mixes. Because of using dry aggregate, the water absorbed by aggregate should be calculated and added to the measured mixing water to make the aggregate in saturated surface-dry condition[42]. This recommendation was applied to the reference mixes and to mixes that contain treated coarse aggregate (oil-soaked and painted). Another twelve mixes were made with dry coarse aggregate (original and treated). The slump test (ASTM C143)[43] was conducted for all the twenty-four mixes and the results are shown in Fig. 5.

[40] Hewlett, P. (Editor), *Lea's Chemistry of Cement and Concrete*, 4th ed., Elsevier, UK, 2004, 1057 pp.
[41] Xie, P., and Beaudoin, J. J. "Effect of Transition Zone Microstructure on Bond Strength of Aggregate-Portland Cement Paste Interfaces" Science and Technology of Overseas Building Materials, V.14, No. 2, 1993, pp. 51-53.
[42] ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete - ACI 211.1-91 (Reapproved 2002)" ACI Manual of Concrete Practice, USA, 2004, 38 pp.
[43] American Society for Testing and Materials, "Standard Test Method for Slump of Hydraulic-Cement Concrete, ASTM C 143/C 143M – 05a" Annual Book of ASTM Standards, 2006, 0402, USA, 4 pp.

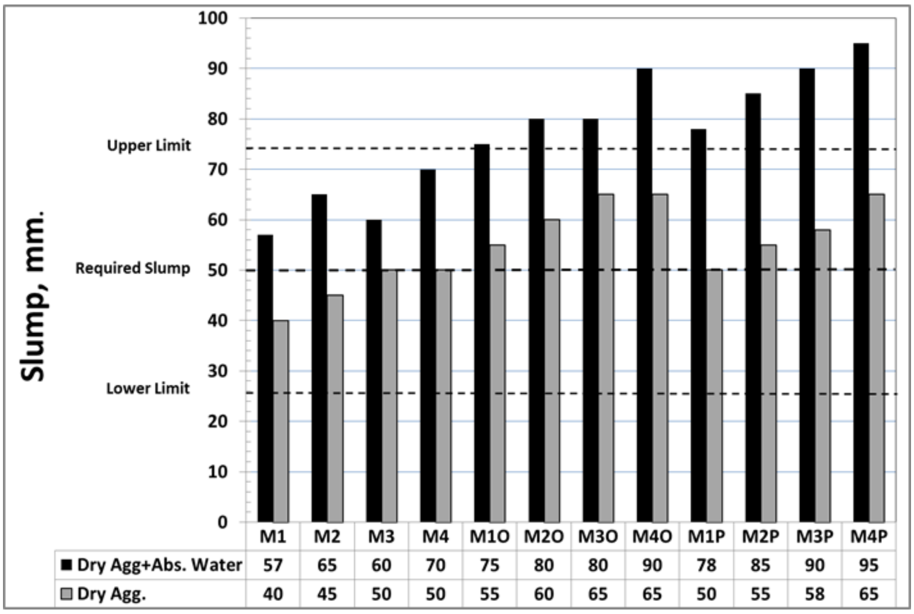

Fig. 5: Slump test results.

These results show that, for the treated aggregate mixes, adding the absorption water to the dry aggregate had increased the workability to values that were beyond the upper limits of the chosen slump. The significant reduction in absorption values for treated coarse aggregate was the main reason for this behavior and almost all the added absorption water for coarse aggregate could be considered as free water in the mix[44]. Meanwhile, mixes contain dry untreated coarse aggregate behaved as expected and the added absorption water kept the workability within the chosen limits. According to that, it was decided to adjust the water content (adding absorption water) only for the reference mixes (mixes M1-M4).

Strength Development

The results of compressive and tensile splitting strength for all mixes are listed in Table 4. All mixes showed continuous gain of strength but with different rates and final magnitude.

The reference mixes, made with untreated coarse aggregate, have the higher compressive and tensile strength values when compared to mixes made with treated aggregate at the same ages. It is believed that the surface coatings of the treated coarse aggregate had caused the recorded decrease in strength.

[44] Shafiq, N., Nuruddin, M. F., and Kamaruddin, I. “Effectiveness of Used Engine Oil on Improvement of Properties of Fresh and Hardened Concrete” Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference, 2006, Malaysia, pp. B159-B166.

Table 4: Strength results

Mix	Compressive Strength, MPa, At Ages:					Splitting Tensile Strength, MPa, At Ages:				
	7d	28d	60d	90d	180d	7d	28d	60d	90d	180d
M1	37.87	58.20	63.32	64.97	66.85	3.81	4.73	5.91	5.96	6.22
M2	30.15	48.76	54.36	56.41	56.92	2.59	3.88	4.27	4.46	4.55
M3	24.42	36.66	42.06	43.48	44.37	2.16	3.03	3.37	3.37	3.41
M4	20.18	28.94	34.86	37.05	37.94	1.54	2.44	2.79	2.87	2.93
M1O	36.40	55.70	61.70	64.22	66.20	2.85	4.22	5.35	5.48	5.65
M2O	28.80	47.20	52.90	55.44	56.72	1.93	3.43	3.84	4.07	4.16
M3O	22.41	35.00	40.95	42.36	43.82	1.57	2.66	3.02	3.06	3.08
M4O	18.80	27.33	34.13	36.63	37.47	1.13	2.12	2.49	2.59	2.62
M1P	35.03	54.14	58.48	59.54	61.33	2.51	3.84	4.79	4.89	5.03
M2P	28.13	45.62	50.6	52.31	52.64	1.68	2.92	3.43	3.59	3.62
M3P	22.65	33.93	38.8	40.14	40.89	1.39	2.41	2.69	2.71	2.73
M4P	18.95	26.67	32.13	34.09	34.83	0.99	1.93	2.21	2.28	2.32

Table 5 shows the strength ratios for treated aggregate mixes to the corresponding reference mixes.

For compressive strength comparisons, two behaviors could be observed related to the type of surface coating. For oil-soaked coarse aggregate mixes, as shown in Fig. 6, there were considerable differences in strength at early ages when compared to reference mixes. Later (at ages more than 28 days) these differences began to decrease and the strength ratios approached to one. Moreover, checking the specimens after testing visually showed the losing of oil film and many broken coarse aggregate particles especially at later ages (90-day and older).

Table 5: Ratio of compressive strength for different mixes

Mix	Compressive Strength Ratio at Ages:				
	7d	28d	60d	90d	180d
M1O/M1	0.961	0.957	0.974	0.988	0.990
M2O/M2	0.955	0.968	0.973	0.983	0.996
M3O/M3	0.918	0.955	0.974	0.974	0.988
M4O/M4	0.932	0.944	0.979	0.989	0.988
M1P/M1	0.925	0.930	0.924	0.919	0.917
M2P/M2	0.933	0.936	0.931	0.927	0.925
M3P/M3	0.928	0.926	0.922	0.923	0.922
M4P/M4	0.932	0.922	0.922	0.920	0.918

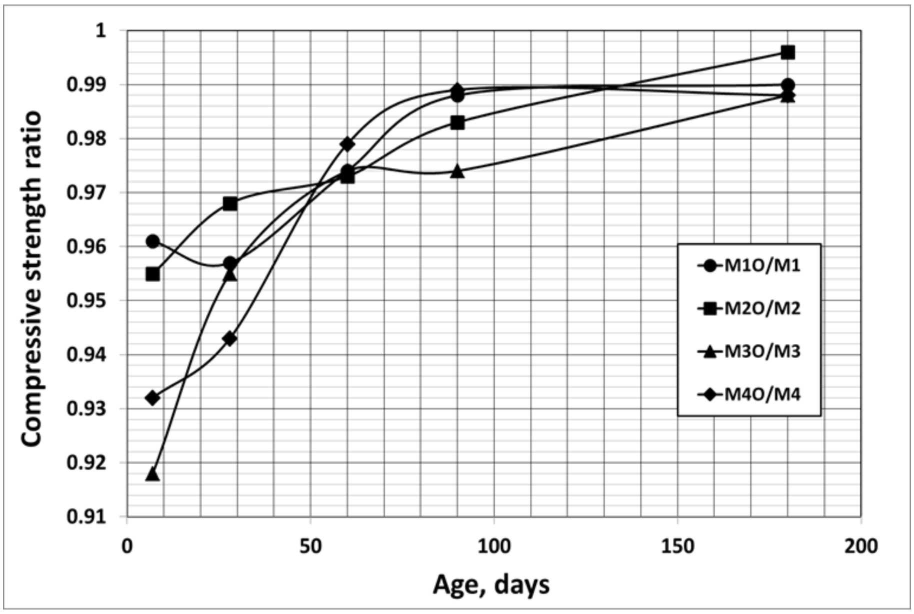

Fig. 6: The variation of compressive strength ratio with age for oil soaked aggregate mixes.

This behavior could be a result of:

a. At early age the surface coating for oil-soaked coarse aggregate acted as a lubricant and reduced the friction between aggregate and cement mortar. Therefore, due to poor bond mixes (M1O – M4O) suffered a significant reduction in strength. Also, the thin film of oil had neutralized the effect of aggregate characteristics (crushed or uncrushed) on strength and only the paste characteristics (w/c ratio and cement content) were dominant.

b. When hydration proceeded at later ages, the thin film of oil could be lost either by dispersion in pore solution[45][46] or by the heat of hydration[47]. Thus, there were insignificant differences in strength.

For painted coarse aggregate (Fig. 7), rich mixes (M1P, M2P) got their maximum ratios of strength at the age of 28 days. Between 28 and 180 days the strength of these mixes began to divert negatively (decrease) from that of corresponding reference mixes. The rate of divergence was steeper in the interval (28 -90) days than beyond this interval.

Leaner mixes (M3P, M4P) attained their highest strength ratio earlier than rich mixes, at the age of 7 days. After that there was a continuous decrease in ratios but with less steeper rate than rich mixes. The tested specimens when checked visually showed that the failure

[45] Abdelaziz, G. E., "Utilization of Used Engine Oil in Concrete as a Chemical Admixture", HBRC Journal, Egyptian Housing and Building National Research Centre, V. 5, No. 3, Dec. 2009.
[46] Shafiq, N., Nuruddin, M. F., and Beddu, S. "Properties of Concrete Containing Used Engine Oil" International Journal of Sustainable Construction Engineering & Technology, V. 2, Issue 1, 2011, pp. 72-82.
[47] Ayininuola, G. M. "Influence of Diesel Oil and Bitumen on Compressive Strength of Concrete" Journal of Civil Engineering (IEB), V. 37, No. 1, 2009, pp. 65-71.

path was always through the contact (interface) zone between coarse aggregate and mortar and through cement mortar. The paint layer had partially cracked in different directions up to the age of 90-day and separated from aggregate (and sometimes was adhered to the mortar) at the age of 180-day.

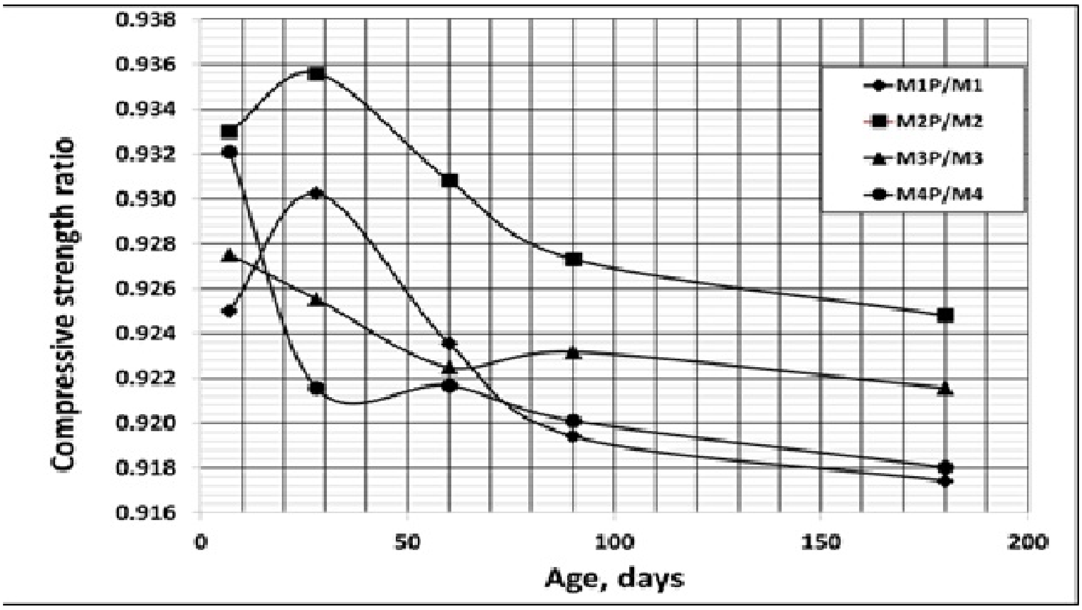

Fig. 7: The variation of compressive strength ratio with age for painted aggregate mixes.

The prescribed behavior may be attributed to:

a. The paint coating layer was successful in eliminating bond between coarse aggregate and cement mortar just as the case of oil-soaking but with higher degrees (lower strength ratios were calculated for the same ages).

b. In leaner mixes, a higher aggregate content would lead to lower shrinkage and lower bleeding, and therefore to less damage to the bond between the aggregate and the cement paste; likewise, the thermal changes caused by the heat of hydration of cement would be smaller[48]. Another factor is the increase of slump, which improves the workability of fresh concrete, and this resulted in effective compaction and less air content.

c. The final decrease in strength could be a result to the long-term exposure of painting layer to internal moisture. This exposure caused the layer to absorb moisture from the mortar and that caused the weakening of the layer and strengthening of surrounding mortar especially if one keeps in mind that normal strength concrete has

[48] Neville, A. M., *Properties of Concrete*, 4th ed., Pearson Education Limited, UK, 2004, 844 pp.

considerable values of water absorption. Therefore, at later age the painting layer separated and caused earlier failure of concrete.

Evaluation of Bond between Coarse Aggregate and Cement Mortar

The cement-aggregate bond results from some combination of mechanical interlocking of hydration products with the aggregate surface and chemical reaction between aggregate and cement paste. Although the aggregate are considered to be inert but evidence of chemical reactions had been reported by many investigators[49].

The present experimental part was designed to manifest the effect of the bond lose due to coarse aggregate coatings on the overall strength of concrete. In other words, all the parameters were kept constant and only the effect of coating was studied. Both bond sources, mechanical interlocking and chemical reaction, were intended to be neutralized by applying coatings to coarse aggregate.

According to the reviewed results, treating coarse aggregate with paint was more effective than oil-soaking in eliminating bond between aggregate and mortar. Similar trends for engine oil effect on concrete strength had been reported by many researchers[50] [51]. Therefore, the following discussions will include reference and painted coarse aggregate mixes only.

The following formula is proposed here to evaluate bond strength:

$$f_{bit} = f_{Mit} - f_{MPit} \qquad (1)$$

Where:

f_{bit}: Estimated bond strength between coarse aggregate and cement mortar for mix *i* at age *t* (days), MPa.

f_{Mit}: Compressive strength for reference mix *i* at age *t* (days), MPa.

f_{MPit}: Compressive strength for painted coarse aggregate mix *i* at age *t* (days), MPa.

Table 6: Values of estimated bond strength and bond to tensile strength ratios

Mix	Estimated Bond Strength, MPa, at Ages:					Bond to Tensile Strength ratio, at Ages:				
	7d	28d	60d	90d	180d	7d	28d	60d	90d	180d
M1	2.84	4.06	4.84	5.43	5.52	0.745	0.858	0.819	0.911	0.887
M2	2.02	3.14	3.76	4.10	4.28	0.780	0.809	0.881	0.919	0.941
M3	1.77	2.73	3.26	3.34	3.48	0.819	0.901	0.967	0.991	1.021
M4	1.23	2.27	2.73	2.96	3.11	0.799	0.930	0.978	1.031	1.061

[49] Struble, L., Skalny, J., and Mindess, S. "A Review of the Cement- Aggregate Bond" Cement and Concrete Research, V. 10, 1980, pp. 277-286.

[50] Shafiq, N., Nuruddin, M. F., and Kamaruddin, I. "Effectiveness of Used Engine Oil on Improvement of Properties of Fresh and Hardened Concrete" Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference, 2006, Malaysia, pp. B159-B166.

[51] Ayininuola, G. M. "Influence of Diesel Oil and Bitumen on Compressive Strength of Concrete" Journal of Civil Engineering (IEB), V. 37, No. 1, 2009, pp. 65-71.

Table 6 displays the values of estimated bond strength between coarse aggregate and cement mortar and the bond to tensile strength ratios for the investigated mixes.

According to Tables 4 and 6, the following remarks could be stated:

a. The estimated bond strength at any time ranged from (6.1 - 8.4) percent of compressive strength for the investigated concrete. Meanwhile, the splitting tensile strength ranged from (7.6 - 10.1) percent of compressive strength.

b. If only the strength values at 28 days are considered, the aforementioned intervals would be narrower (more conservative). The intervals will be (6.4 - 7.8) percent for bond strength and (8.0 - 8.4) percent for tensile strength.

c. The values of bond to tensile strength ratio could be considered as an indication to weather the failure is occurred due to bond lose or because the stresses at interface zone had exceeded the tensile strength. When these values are less than one that means bond strength has controlled the failure. Otherwise, if the ratio is near to unity or more, tensile strength is the governing factor.

Conclusion

1. The bond between cement paste and aggregate depends largely on the interface zone characteristics. The effect of the transition zone on the mechanical and transport properties of concrete is still obscure. This is largely due to the difficulty in measuring the properties of real transition zones. Previously, different test methods and specimens had normally been used for measuring the tensile or shear bond strength between aggregate and cement paste or mortar. All these tests can only be described as a gross simplification of the real situation around interfaces.

2. The present work represents a simple proposed evaluation for the bond between coarse aggregate and cement mortar. The proposed evaluation depends mainly on the results of the uniaxial compression test of concrete which is a simple and standardized test.

3. The effects of engine oil and oil paint as aggregate coatings on bond have been investigated. The paint coating layer was more effective in eliminating bond between coarse aggregate and cement mortar than engine oil.

4. According to the present work, the estimated bond strength at any time ranged from (6.1 - 8.4) percent of compressive strength for the investigated concrete. Meanwhile, the splitting tensile strength ranged from (7.6 - 10.1) percent of compressive strength.

5. The values of bond to tensile strength ratio could be considered as an indication to weather the failure is occurred due to bond lose or when induced stresses exceed the tensile strength of concrete. When these values are being less than one that means bond strength has

controlled the failure. Otherwise, if the ratio is near to unity or more, tensile strength is the governing factor.

References:

Appa Rao, G., and Raghu Prasad, B. K. "Influence of Interface Properties on Fracture Behavior of Concrete" Sadhana (Indian Academy of Sciences), V. 36, Part 2, 2011, pp. 193-208.

Struble, L., Skalny, J., and Mindess, S. "A Review of the Cement- Aggregate Bond" Cement and Concrete Research, V. 10, 1980, pp. 277-286.

Van Mier, J. G. M., and Vervuurt, A. " Engineering and Transport Properties of the Interface Transition Zone in Cementitious Composites –

Test Methods and Modelling for Determining the Mechnical Properties of the ITZ in Concrete" RILEM Publications, Report No. 20, 1999, pp. 19-52.

Alexander, M. G., Mindess, S., Diamond, S., and Qu, L. "Properties of Paste-rock Interfaces and Their Influence on Composite Behaviour" Materials and Structures, V.28, 1995, pp. 497-506.

Neville, A. M., *Properties of Concrete*, 4th ed., Pearson Education Limited, UK, 2004, 844 pp.

Avram, C., Facaoaru, I., Filimon, I., Mirsu, O., and Tertea, I., *Concrete Strength and Strains*, Elsevier, New York, 1981, 558 pp.

Newman, J., and Choo, B. S., *Advanced Concrete Technology* - *Concrete Properties*, Elsevier, UK, 2003, 314 pp.

American Society for Testing and Materials, "Standard Specification for Portland Cement, ASTM C 150 – 05" Annual Book of ASTM Standards, 2006, 0402, USA, 8 pp.

American Society for Testing and Materials, "Standard Specification for Concrete Aggregates, ASTM C 33 – 03" Annual Book of ASTM Standards, 2006, 0402, USA, 11 pp.

ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete - ACI 211.1-91 (Reapproved 2002)" ACI Manual of Concrete Practice, USA, 2004, 38 pp.

American Society for Testing and Materials, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate, ASTM C 127 – 04" Annual Book of ASTM Standards, 2006, 0402, USA, 6 pp.

American Society for Testing and Materials, “Standard Test Method for Slump of Hydraulic-Cement Concrete, ASTM C 143/C 143M – 05a” Annual Book of ASTM Standards, 2006, 0402, USA, 4 pp.

American Society for Testing and Materials, ” Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM C 39/C 39M – 05” Annual Book of ASTM Standards, 2006, 0402, USA, 7 pp.

American Society for Testing and Materials, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM C 496/C 496M – 04” Annual Book of ASTM Standards, 2006, 0402, USA, 5 pp.

Hewlett, P. (Editor), *Lea’s Chemistry of Cement and Concrete,* 4th ed., Elsevier, UK, 2004, 1057 pp.

Xie, P., and Beaudoin, J. J. “Effect of Transition Zone Microstructure on Bond Strength of Aggregate-Portland Cement Paste Interfaces” Science and Technology of Overseas Building Materials, V.14, No. 2, 1993, pp. 51-53.

Shafiq, N., Nuruddin, M. F., and Kamaruddin, I. “Effectiveness of Used Engine Oil on Improvement of Properties of Fresh and Hardened Concrete” Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference, 2006, Malaysia, pp. B159-B166.

Abdelaziz, G. E., “Utilization of Used Engine Oil in Concrete as a Chemical Admixture”, HBRC Journal, Egyptian Housing and Building National Research Centre, V. 5, No. 3, Dec. 2009.

Shafiq, N., Nuruddin, M. F., and Beddu, S. “Properties of Concrete Containing Used Engine Oil” International Journal of Sustainable Construction Engineering & Technology, V. 2, Issue 1, 2011, pp. 72-82.

Ayininuola, G. M. “Influence of Diesel Oil and Bitumen on Compressive Strength of Concrete” Journal of Civil Engineering (IEB), V. 37, No. 1, 2009, pp. 65-71.