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Using AP2RC & P1RB micro-silica gels to improve concrete strength and study of resulting contamination

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Abstract. Today, application of additives to replace cement in order to improve concrete mixes is widely promoted. Micro-silica is among the best pozzolanic additives which can desirably contribute to the concrete characteristics provided it is used properly. In this paper, the effects of AP2RC and P1RB micro-silica gels on strength characteristics of normal concrete are investigated. Obtained results indicated that the application of these additives not only provided proper workability during construction, but also led to increased tensile, compressive and flexural strength values for the concrete during early ages as well as ultimate ones with the resulting reduction in the porosity lowering permeability of the micro-silica concrete. Furthermore, evaluation of microbial contamination of the mentioned gels showed the resultant contamination level to be within the permitted range.

Keywords: concrete admixture; concrete additive; silica fume gel; tensile strength; compressive strength; flexural strength; microbial contamination

1. Introduction

Concrete is one of the most consumed construction materials which have been always attracted attention of researchers due to its adaptability with diverse construction conditions and application context of different structures. In spite of numerous advantages of concrete such as its remarkable compressive strength, its weaknesses such as failure to tolerate tension and flexure, cracking and high amount of pores have caused many studies to be performed on achieving proper and optimum concrete composition. Additives are among common solutions for obtaining a better performance for concrete and enhancing its workability. Such materials are used whether as admixtures without changing concrete composition or they may be used as a substitute for part of cement within concrete in order to improve and economize concrete mixture. Natural and manufactured pozzolans are among the most highlighted cement substitute additives. Volcanic ash, opaline shale, limestone and meta-kaolinite are examples of natural pozzolans, while micro-silica, fly ash (or Pulverized Fuel Ash (PFA)), rise husk ash and metal extraction furnaces slag-as industrial by-

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products-constitute main manufactured pozzolans. Pozzolans contribute to mechanical and chemical characteristics of cement mortar through formation of hydrated calcium silicate. In contrast to the hydrated lime being soluble in water, this is a stable substance (Holland *et al*. 1995, Dotto *et al*. 2004).

Micro-silica is one of the newest manufactured pozzolanic materials, first employed in Norway and afterward systematically utilized all over North America and Europe since early 1980s. It is now one of the best mineral additives for concrete mixtures. Micro-silica is a mainly amorphous siliceous material which is spherical in shape. It is a by-product of silicon metal or silicon containing alloys, especially fero-siliceous, manufacturing process with its particle size being 50–100 times smaller than that of cement particles. It acts as the filling material between cement components and acts not only to adhere cement particles to each other, but also to increase adhesion between the cement and rock aggregates, while contributing to the cement lifetime via reducing pore space, i.e., permeability (Poon *et al.* 2006, Duan *et al.* 2013). Rapid increase in the application of micro-silica may be attributed to its favorable impacts on mechanical properties of cement composites. Results of performed experiments (Cong *et al.* 1992, Nehdi *et al.* 2004, Razak and Wong 2005, Ganjian and Pouya 2009) indicated that micro-silica can increase cement strength, with the amount of such an increase being dependent on the cement type, amount of micro-silica, compactor type and treatment procedure. Such an enhancement in the strength is obtained by the physical and chemical effects of micro-silica on the concrete. Substitution of cement with micro-silica in concrete mixes will contribute to yield stress and viscosity of the resultant concrete. Vikan *et al*. (2003) have shown that substituting up to 10% of the cement weight with micro-silica within concrete mixture may increase yield stress in concrete mortars, which was obtained by analysing the flow curves with the linear Bingham approach for a medium and low shear rate range. Park *et al.* (2005) found that using micro-silica to substitute 5, 10 and 15% of the cement may lead to yield stress as well as plastic viscosity to be increased. They suggested that micro-silica shall be used to increase plastic viscosity, and hence to reduce separation effect where drastic increase in yield stress could be compensated by a triple mixture of cement material with either fly ash or slang. Generally, due to its small particles, micro-silica may increase concrete mix adhesion causing concrete particles separation and flowing characteristics to be reduced (Elahi *et al.* 2010).

Effect of micro-silica on mechanical and durability properties of different curing ages of 7, 28, 56 and 91 days for high volume fly ash recycled aggregate concretes was investigated by Shaikh *et al*. (2015). Their results showed that strength properties of the early age improved with adding 10% silica fume, while all mechanical properties of later ages improved for 5, 10 and 15% silica fume. Zhang *et al*. (2016) studied the effect of raw and densified silica fume in the paste, mortar and concrete. The results showed that adding silica fume leads to an increase in the hydration degree of paste, increase in compressive strengths of hardened pastes, mortars and concretes, and improvement in properties of inerfacial transition zone of concrete. In addition, raw silica fume is better dispersed compared to densified silica fume in paste; while both of them are good dispersed in concrete. Zhang *et al*. (2016) studied the effect of silica fume on fresh properties, compressive strength and fracture behavior of fly ash concrete composite. They found that the 28-day compressive strength and fracture parameters increased and decreased with the addition of silica fume, respectively. To evaluate the compressive strength, density, water permeability, static modulus of elasticity, dynamic modulus of elasticity and chloride diffusion of waste rubber fiber concrete with and without silica fume, some tests were conducted by Gupta *et al*. (2016). They concluded that replacement of 10% cement by silica fume does not result in significant loss in strength and durability properties. Barati *et al*. (2016) experimentally evaluated the effect of various mix designs and different percentages of micro silica gel (a combination of micro silica and super-lubricant) on roller compacted concrete pavement.

Substituting a small amount of cement by micro-silica contributes to its performance characteristics and stability. However, it may have some destructive impacts on behavioral characteristics of concrete if too much micro-silica is engaged. Based on experimental work, Valipour *et al.* (2013) proposed an optimum percentage of micro-silica employment to be 7.5-10 percent of the cement weight. Silica fume concrete may cause a decrease in permeability with respect to chlorine and sulfate ions (Stark 1982, Bouzoubaa *et al.* 2004, Gesoğlu *et al.* 2009), so it is suitable for concreting sea piers, piles, pillars and pre-manufactured parts. Higher frosting durability (Mazloom *et al.* 2004) as well as hardness capacity and compaction (Köksal *et al.* 2008), lower concrete transpiration due to consumption of free water for wetting very small surfaces of silica fume particles (Khayat and Mitchell 2009) and economic benefits for bridging, bottoming and railway construction projects by reducing required thickness of the slab due to increased tensile strength (Jaturapitakkul *et al.* 2004) are just some of other advantages of micro-silica bearing concretes.

Positive contributions of silica-fume into various characteristics of the concrete in one hand, and its associated problems in the other hand have caused silica-fume powder to be substituted by silica-fume gel. As mentioned before, silica-fume particles are hundreds of times smaller than those of conventional Portland cements. In order to prevent excessive concentration of micro-silica in a part of concrete, and also considering problems associated with its shipment and storage as a powdered material and to further eliminate working personnel safety hazards, silica fume can be used in a gel form. Accordingly, in order to investigate silica fume gel performance, effects of two types of micro-silica gel with commercial designations of AP2RC and P1RB, respectively, on the tensile, compressive and flexural strength of a concrete made of conventional Portland cement are addressed in this paper. While the effects of silica fume in powder form on concrete parameters have been investigated so far, the impacts of micro-silica gel AP2RC and P1RB produced by Fabir Co have not been studied yet. In addition, their corresponding possible microbial contaminations are also considered and the results are compared to the standard values established by U. S. Environmental Protection Agency. In this study, cylindrical specimens are used to investigate the tensile strength, while prismatic specimens were employed to assess compressive and flexural strengths. Aggregate material grading was performed according to ASTM-C136 while consumed material specifications and concrete mixing scheme was obtained from ACI-211.

2. Experimental program

In this study, effects of two types of micro-silica gel produced by a domestic manufacturerunder class names of AP2RC and P1RB, on compressive, tensile and flexural strengths of concrete and quality are investigated before being compared to those of an additive-free concrete (the control). Possible contaminating impact of micro-silica gel within concrete water tanks was evaluated using microbial contamination experiments based on standard method. Aggregate grading was performed according to ASTM-C138 procedure with a maximum grain size of 19 mm within standard range. Consumed material specifications and concrete mixing scheme were adopted from ACI-211 for 28-days strength (f'_c=35 MPa) and are calculated and reported in Tables 2 and 3.

2.1 Material specifications and concrete mixing scheme

2.1.1 Consumed material

Consumed material for preparing concrete mixtures (Table 1) included Tehran type 2 cement, natural aggregates from producing mines located at the west of Tehran and potable water. Micro-silica gels were produced by a domestic manufacturer (Fabir Co) and included mixed micro-silica gel and ultra-plasticizers. AP2RC class products are designed to build impermeable concretes with reduced plastic cracks and enhanced relative compressive, tensile and flexural strength values. It is particularly used in watertight sealing concretes. In terms of physical properties, it is in gel form when it is stationary while it turns to a viscose liquid state as soon as it is mobilized. It has a grey color with a specific weight of 1.3 g/cm^3. It has no chloride or nitrate while it freezes at 0ºC. Micro-silica gel of P1RB, on the other hand, is designed to produce anti-abrasion concrete, water proof concrete, concrete tankers, high-strength concrete and special quality mortars. Similar to AP2RC, this material is in gel form when it is stationary while it turns to a viscose liquid state as soon as it is mobilized. It has a grey color with a specific weight of 1.4 g/cm^3. It has also no chloride or nitrate with its freezing point at 0ºC.

Table 1 Specifications of consumed material for different concrete mixtures

No.	Material	Specifications
1	Cement	Tehran Type 2
2	Mixing water	Potable Water
3	Aggregates	Aggregate producing mines on the west of Tehran
4	Micro-silica gel	AP2RC and P1RB classes (Fabir Co)

2.1.2 Concrete mixing scheme via ACI-211 procedure

In this research, three different mixing schemes with different gel percentages were considered in order to study the effect of micro-silica gel on the performance of fresh concrete, water absorption and concrete strength as well as its associated contamination within concrete water tanks. All schemes were mixed with the same cement type and the same type and amount of aggregates where consumed water and water-cement ratios were assessed for different percentages

Table 2 Composition of different mixing schemes

No.	Mixing scheme	W/C	Fresh concrete density (kg/m^3)	Slump (mm)	Cement grade (kg/m^3)	Water (kg/m^3)	Gravel	Sand	Gel to cement ratio (w %)
1	No gel (Control)	0.54	2387	80	380	205	805	960	0
2	With gel (AP2RC)	0.46	2442	80	380	175	805	960	3
3	With gel (P1RB)	0.39	2384	80	380	148	805	960	5

of micro-silica gel (0-5%) and constant workability provision (80 mm slump). Mixing properties are demonstrated in Table 2.

According to the manufacturer's recommendation, ratios of 2-3% and 5-8% of used cement weight are utilized respectively for AP2RC and P1RB gels to be added to the concrete samples. Less amounts of these gels in concrete would lead to a poor performance of the ability as a plasticizer, a faster decline in flowing ability, the absorption of free lime content and so on. Also evaluating on positive or negative influence of more amounts of these gels would need additional tests to be conducted. So in this study, three and five percent of cement weight were used respectively for AP2RC and P1RB gels added to the mixture in the samples.

2.2 Sampling and experimental methodology

Concrete preparation and storage were performed conforming to ASTM-C192. In order to add micro-silica gel into the concrete mix, an amount of water was first added to be blended with the aggregates before gel was added to the concrete in a mix with the remaining amount of water. In

Fig. 1 Prismatic specimens for determination of flexural and compressive strengths

(a) Test samples

(b) Close-up of the specimens

Fig. 2 Cylindrical specimens for the Brazilian test to measure tensile strength

Fig. 3 Brazilian test for tensile strength measurements

order to conduct flexural strength tests (modulus of rupture), a prismatic specimen (Fig. 1) of 50×10×10 cm was used through two point loading method. Cylindrical specimens (Fig. 2) of 10 cm diameter and 20 cm height were used in order to evaluate tensile strength of the concrete (Brazilian method[1], Fig. 3), while post-flexural test prismatic specimens were used to determine compressive strength of the concrete.

Specimen strength values were tested at the ages of 7 and 28 days under conditions of specimen treatment inside a water pool at ambient temperatures of 23 and 25ºC, respectively. For the sake of calculating water absorption value for the concrete specimens, they were weighted at an age of 28 days before being dried under saturation with dry surface conditions at 110ºC for 24 hours. Compressive and tensile strengths of the specimens were measured by a pressurized hydraulic jack of 500-2000 kN capacity, while flexural strength was measured via two point loading procedure with a pressurized hydraulic jack of 50-100 kN loading capacity. In order to investigate microbial contamination of the concretes with micro-silica gel additives, a concrete pool of 25×40×40 cm were constructed using micro-silica gel bearing concrete. At the end of a 28-days treatment period, bacteriological examinations were performed along with HPC2 on the stored water inside the previously constructed water pools via the standard method. The results of microbial contamination examinations are reported in Table 4.

3. Results and interpretations

3.1 Physical properties and mechanical strength test results

The results of compressive, flexural and tensile strengths of the specimens are summarized in Table 3 and Fig. 4. As shown, generally due to completion of hydration process throughout the time, strength values exhibit an increasing trend with time and at any given age, the concrete

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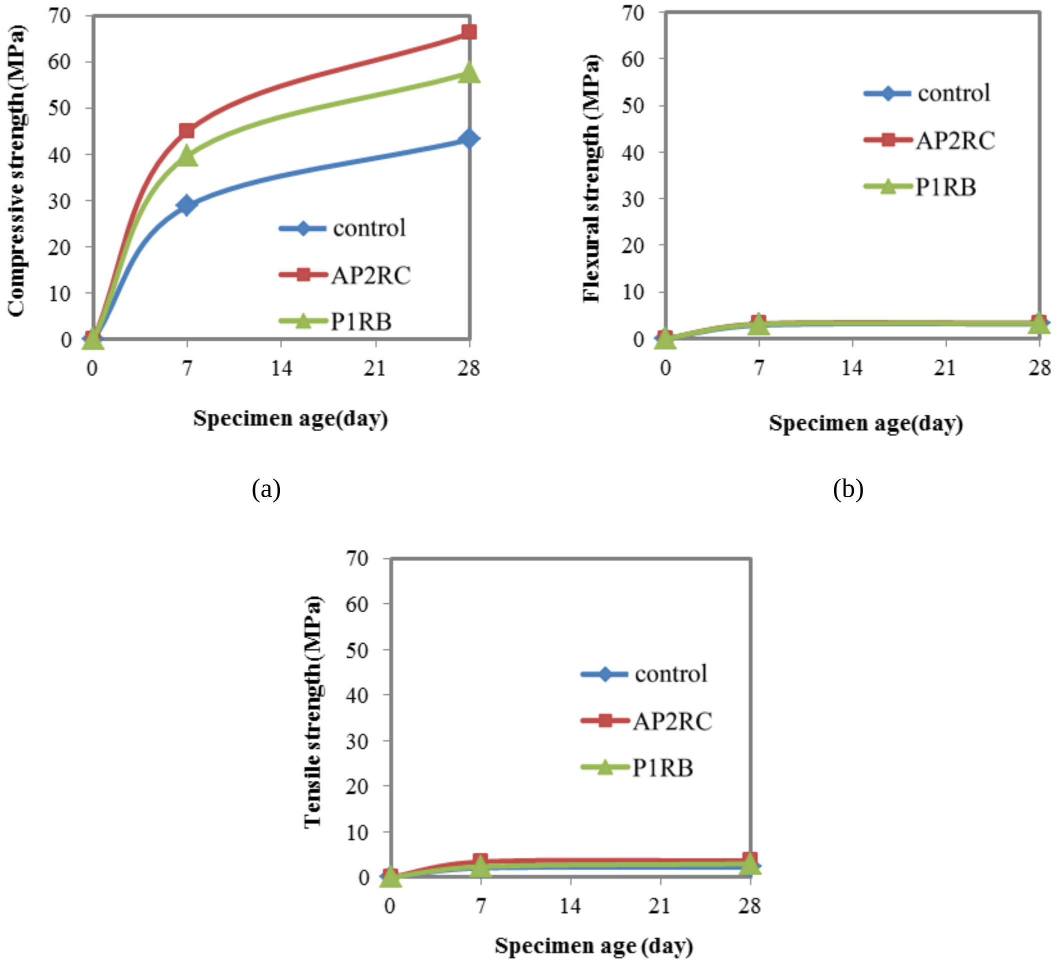
[1] In practice, the cylindrical specimen was subjected to a compressional load along its diameter while its tensile strength was measured.

[2] 9215 Heterotrophic Plate Count – 2004

Table 3 Test results of compressive, flexural and tensile strength as well as water absorption for concrete with different amounts of micro-silica gels

No.	Mixing scheme	Specimen age (days)	Hardened concrete density (kg/m^3)	Cubic compressive strength (MPa)	Flexural strength (MPa)	Brazilian tensile strength (MPa)	Gel to cement ratio (%)	Water absorption of concrete (%)
1	No gel (control)	7	2355	28.82	2.88	2.07	0	-
2		28	2351	43.23	3.17	2.23	0	4.5
3	With gel (AP2RC)	7	2414	45.00	3.18	3.44	3	-
4		28	2439	66.18	3.31	3.69	3	3.6
5	With gel (P1RB)	7	2354	39.71	3.1	2.36	5	-
6		28	2391	57.65	3.24	2.99	5	4.1



(a)

(b)

(c)

Fig. 4 Variation of strength versus specimen age. (a) compressive, (b) flexural (c) tensile specimen with 3% of micro-silica gel (AP2RC class) has higher compressive, flexural and tensile strengths compared to other specimens made by the concrete with 5% of micro-silica gel (P1RB) whose strength values are still in turn higher than those of the control samples. This may be attributed to the decrease in the porosity of the concrete.

According to investigations previously performed by Fabir Company. The flexural and tensile strengths are to be the same for the same percent of AP2RC and P1RB gels in the concrete mix. However, experimental results indicated that introducing AP2RC and P1RB gels of 3% and 5% (with respect to the cement weight), respectively, were associated with almost the same amount of increase in the value of flexural strength, while a higher increase was evident in the value of tensile strengths in the case of AP2RC.

Another research performed by the company (Fabir Co) showed that compressive strength of the concrete was almost the same for the same percent of both P1RB and AP2RC gels within early ages (up to 3 days), while a higher strength was achieved by the samples containing P1RB within longer ages. Once again, experimental results indicated that although the compressive strength was the same for both P1RB and AP2RC gels within early ages, considering the percentages used in this study within longer ages, more increase was evident in the compressive strength of the samples containing AP2RC rather than those containing P1RB. In both types of gels used, a reduction in water-cement ratio was associated with a reduction in concrete porosity over bulk paste as well as common area between the aggregates and the paste. Such a reduction in porosity was definitely the most affecting parameter on the resultant strength and durability increased remarkably. Water absorption test results were also indicative of more reduction in water absorption along with concrete porosity for those specimens having micro-silica gel of AP2RC when compared to either those of P1RB class or those of control sample. It is observed that although using higher percentage of gel (P1RB class) has led to enhanced plasticity and workability as well as lower water to cement ratio due to higher amount of plasticizers in gel, but meanwhile, it has decreased the density, strengths and also water absorption value.

Another issue that can be mentioned is the way control specimen and specimens containing micro-silica gels, fractured. In indirect tensile test (Brazilian test), fracture of the specimens occurred along the diameter, or in other words, along the loading direction due to the tensile stresses created along the specimen diameter (Fig. 5).

Furthermore, in flexural strength test, where the aim is to evaluate the tensile strength of concrete in tension due to bending, tensile cracks develop gradually from the middle third part and the bottom of prismatic specimens resulting eventually in their fracture (Fig. 6).

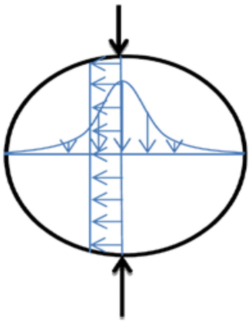
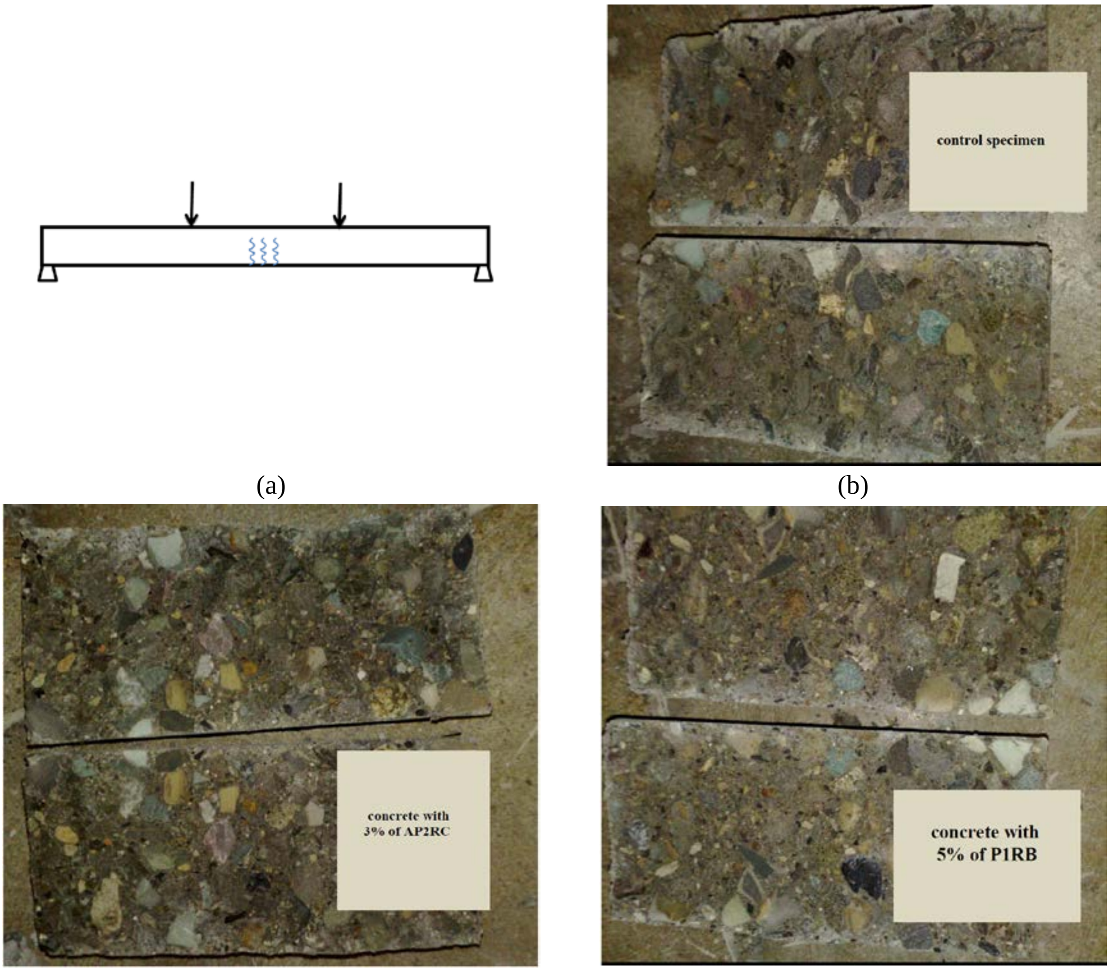


Fig. 5 Schematic stress patterns in Brazilian test



(a) (b)

(c) (d)

Fig. 6 Crack patterns of Prismatic specimens in flexural strength; (a) schematic cracks, (b) control specimen, (c) AP2RC specimen and (d) P1RB specimen

3.2 Microbial contamination examination results

The results of bacteriological tests on water samples obtained from the concrete pools built by micro-silica gel bearing concrete are reported in Table 4. Such tests included stages of sample preparation as well as application of different methods to count microorganisms. The used method is based on acquiring a given volume of sample and its inseminating on the surface of or into a specific culture medium. It is assumed that every microorganism will proliferate after being incubated to form observable colonies within the culture medium. In this method, a given volume or concentration of sample is distributed over agar bearing surface of the culture medium on which all colonies will be counted after incubation. The multiple test method of searching for and counting coliforms in water is one of the reference methods to identify and count coliforms and Fecal coliforms in water via culturing in a liquid medium through multiple method, and then

Table 4 Results of microbial tests on the water samples obtained from the pools built by the micro-silica gel bearing concrete

No.	Sample Type	Total coliform (MPN/100 ml)	Fecal coliform (MPN/100 ml)	HPC (Cfu/1 ml)
1	Potable water	0	0	0
2	Water from the concrete pool built by the concrete with 3% of AP2RC gel	0	0	15
3	Water from the concrete pool built by the concrete with 5% of P1RB gel	0	0	28

calculating their maximum possible number within the sample. Coliforms are micro-organisms which can grow under aerial condition in a liquid lactose medium over temperature range of 35-37ºC to produce acid and gas within 48 hours. Fecal coliforms as well-defined types of coliforms can further produce gas and acid within a 24-hour time pan at a temperature range of 44 to 44.5ºC. Heterotrophic Plate Count (HPC) is a reliable and complementary test for common hygiene indices. It is also a criterion to determine efficiency of water distribution network and treatment processes in microbiologic laboratories. Heterotrophic micro-organisms are those organisms that need organic carbon for their growth and include various bacteria, molds and fungus. Heterotrophic bacteria live naturally inside human body and are fend off via stool. In a HPC test, grown colonies in the specific culture medium for this test are counted and evaluated before being able to judge about the quality of water resource based on the number of colonies. Factors such as incubation temperature, culture medium, culture time span and method tend to influence this test and change grown colonies.

According to a National Iranian Standard, existence of up to 0 MPN/100 ml coliforms and fecal coliforms is permitted. Furthermore, US Environmental Protection Agency (EPA) on its last microbial standard in 2000, specifies the maximum allowed heterotrophic bacteria inside water distribution networks to be 500 cfu/ml (Grabow 1996). Once having more than 500 cfu/ml of heterotrophic bacteria, it is expected to face some conflicts when identifying coliform bacteria within the acquired sample from water distribution system (Pavlov *et al*. 2004).

According to Table 4, the levels of microbial contamination of the water samples obtained from the concrete pools were less than those permitted by the corresponding standards.

4. Conclusions

The importance of obtaining an optimum mix for preparing appropriate concrete has led to numerous studies on composition of concrete mix. According to the conducted tests, it has been revealed that substituting some portion of cement with additives may contribute to better performance of the concrete. Silica fume as a manufactured pozzolan among the best admixtures partly substituted for cement has been used in the concrete in powder or gel form. In order to have better understanding of the impact of this pozzolan on the concrete performance produced by conventional Portland cement, the effects of two silica-fume gels under commercial names of AP2RC and P1RB on the concrete strengths were studied in this paper. The results indicated that introducing AP2RC and P1RB gels of 3% and 5% (with respect to the cement weight), respectively, were associated with 34% and 66% increase in tensile strength, 33% and 53%

improvement in compressive strength and also 2% and 5% rise in flexural strength of the concrete, when compared to those of control sample. Furthermore, considering the porosity and permeability reduction in gel bearing concrete samples which is evident by their strength enhancement and also by investigating microbial contamination of silica fume gels being within the allowed range, one can use silica fume concrete to build liquid containers such as water tanks. Furthermore, AP2RC gel, rather than P1RB is more effective in terms of increasing tensile and flexural strengths of the concrete, so that introducing a lower percent of AP2RC into the concrete will result in higher rises in the strength values.

References

Barati, R., Sahaf, S.A., Jamshidi, M. and Razazpor, A. (2016), "Examining the impact of micro silica gel additive on the compressive strength and water absorption of roller compacted concrete pavement", *MAS*, **10**(5), 194.

Bouzoubaa, N., Bilodeau, A., Sivasundaram, V., Fournier, B. and Golden, D.M. (2004), "Development of ternary blends for high-performance concrete", *ACI Mater. J.*, **101**(1), 19-29.

Cong, X., Gong, S., Darwin, D. and McCabe, S.L. (1992), "Role of silica fume in compressive strength of cement paste, mortar, and concrete", *ACI Mater. J.*, **89**(4).

Dotto, J., De Abreu, A., Dal Molin, D. and Müller, I. (2004), "Influence of silica fume addition on concretes physical properties and on corrosion behaviour of reinforcement bars", *Cement Concrete Compos.*, **26**(1), 31-39.

Duan, P., Shui, Z., Chen, W. and Shen, C. (2013), "Effects of metakaolin, silica fume and slag on pore structure, interfacial transition zone and compressive strength of concrete", *Constr. Build. Mater.*, **44**, 1-6.

Elahi, A., Basheer, P., Nanukuttan, S. and Khan, Q. (2010), "Mechanical and durability properties of high performance concretes containing supplementary cementitious materials", *Constr. Build. Mater.*, **24**(3), 292-299.

Ganjian, E. and Pouya, H.S. (2009), "The effect of Persian gulf tidal zone exposure on durability of mixes containing silica fume and blast furnace slag", *Constr. Build. Mater.*, **23**(2), 644-652.

Gesoğlu, M., Güneyisi, E. and Özbay, E. (2009), "Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag, and silica fume", *Constr. Build. Mater.*, **23**(5), 1847-1854.

Grabow, W. (1996), "Waterborne diseases: Update on water quality assessment and control", *Water S.A.*, **22**(2), 193-202.

Gupta, T., Chaudhary, S. and Sharma, R.K. (2016), "Mechanical and durability properties of waste rubber fiber concrete with and without silica fume", *J. Clean. Prod.*, **112**, 702-711.

Holland, T.C., Detwiler, R., Aïtcin, P.C., Hulshizer, A.J., Ozyildirim, H.C., Arney, D.O. and Pistilli, M.F. (1996), "Guide for the use of silica fume in concrete", *ACI Committee*, **234**.

Jaturapitakkul, C., Kiattikomol, K., Sata, V. and Leekeeratikul, T. (2004), "Use of ground coarse fly ash as a replacement of condensed silica fume in producing high-strength concrete", *Cement Concr. Res.*, **34**(4), 549-555.

Khayat, K. and Mitchell, D. (2009), *Self-consolidating Concrete for Precast, Prestressed Concrete Bridge Elements*, Transp. Res. Board, **628**.

Köksal, F., Altun, F., Yiğit, İ. and Şahin, Y. (2008), "Combined effect of silica fume and steel fiber on the mechanical properties of high strength concretes", *Constr. Build. Mater.*, **22**(8), 1874-1880.

Mazloom, M., Ramezanianpour, A. and Brooks, J. (2004), "Effect of silica fume on mechanical properties of high-strength concrete", *Cement Concr. Compos.*, **26**(4), 347-357.

Nehdi, M., Pardhan, M. and Koshowski, S. (2004), "Durability of self-consolidating concrete incorporating high-volume replacement composite cements", *Cement Concr. Res.*, **34**(11), 2103-2112.

Park, C., Noh, M. and Park, T. (2005), "Rheological properties of cementitious materials containing mineral admixtures", *Cement Concr. Res.*, **35**(5), 842-849.

Pavlov, D., De Wet, C., Grabow, W. and Ehlers, M. (2004), "Potentially pathogenic features of heterotrophic plate count bacteria isolated from treated and untreated drinking water", *J. Food Microbiol.*, **92**(3), 275-287.

Poon, C.S., Kou, S. and Lam, L. (2006), "Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete", *Constr. Build. Mater.*, **20**(10), 858-865.

Razak, H.A. and Wong, H. (2005), "Strength estimation model for high-strength concrete incorporating metakaolin and silica fume", *Cement Concr. Res.*, **35**(4), 688-695.

Shaikh, F., Kerai, S. and Kerai, S. (2015), "Effect of micro-silica on mechanical and durability properties of high volume fly ash recycled aggregate concretes (HVFA-RAC)", *Adv. Concrete Constr.*, **3**(4), 317-331.

Stark, D. (1982), "Longtime study of concrete durability in sulfate soils", *ACI Special Publ.*, **77**, 21-40.

Valipour, M., Pargar, F., Shekarchi, M. and Khani, S. (2013), "Comparing a natural pozzolan, zeolite, to metakaolin and silica fume in terms of their effect on the durability characteristics of concrete: A laboratory study", *Constr. Build. Mater.*, **41**, 879-888.

Vikan, H., Justnes, H., Wallevik, O. and Nielsson, I. (2003), "Influence of silica fume on rheology of cement paste", *3rd International Symposium on Self-Compacting Concrete*.

Zhang, P., Gao, J.X., Dai, X.B., Zhang, T.H. and Wang, J. (2016a), "Fracture behavior of fly ash concrete containing silica fume", *Struct. Eng. Mech.*, **59**(2), 261-275.

Zhang, Z., Zhang, B. and Yan, P. (2016b), "Comparative study of effect of raw and densified silica fume in the paste, mortar and concrete", *Constr. Build. Mater.*, **105**, 82-93.

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