Physico-mechanical characterization of high-volume fly ash cement paste composites

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Abstract. The current annual worldwide production of coal ash is estimated at one billion tons of which at least 70-75% is fly ash. A huge amount of such wastes can seriously damage the environment and ecology of the planet. In this study, a high volume of fly ash was used to produce environmentally friendly building products. The composites were designed as pure cement, and as a result, no aggregates were used. Composites are classified as non-load-bearing elements in the construction sector. Physico-mechanical characterisation of laboratory-produced composites was evaluated based on dry density, water absorption, apparent specific gravity, porosity, and compressive and flexural strength tests. Based on the test results, fly ash can be used as an alternative binder for building products. Water absorption test results of composites produced by 40% fly ash showed satisfactory results. Dry density measurements proved the lightweight nature of the composites. Compressive and flexural strength test results were within the limit specified by the international authorities in the building sector. The composites comprising 60% fly ash attained 30 Mpa compressive strength at 28 days. The produced samples can be used effectively for various civil engineering works. The utilisation of fly ash in construction could reduce the carbon dioxide emission and produce a better sustainable solution.

1. Introduction

Many research studies have been conducted on high volume fly ash (HVFA) optimization in cementitious composites since the 1970s [1]. The utilization of fly ash as a binder in cement paste and mortar applications has increased rapidly in the 2000s [2], and this trend is assumed to continue in the upcoming periods due to the industrial and technical feasibility [3]. To universally recognize fly ash in cement and concrete as an alternative binder material depends on a detailed understanding of its performance both in the fresh and hardened state [4]. A significant achievement has been reached in recent years based on various evaluating techniques that have been used to characterize fly ash to fulfil its possible applications in bulk utilization. These evaluations assessed appropriate physico-chemical properties, such as chemical stability against the aggressive environment, carbon content, particle size distribution, water absorption, pozzolanicity, and porosity [5]. However, the aforementioned properties have not fully satisfied the criteria adopted by international authorities for evaluating the overall quality of the pure cement composites. This might be because of unsatisfactorily analyzing the properties of fly ash in real and standard testing applications [6].

Many studies have indicated that adding fly ash to cement paste and mortar mixes results in decreased frictional forces among the particles and thus improved flow characteristics [7], excellent pumpability, and reduced tendency of water gain [8]. Many previous studies have mentioned that the decrease in water demand is because of “ball-bearing effects of spherical fly ash particles” [9]. Helmuth suggested that “flocculation and dispersion effects” are more important than the “lubricating effects” in water reduction of spherical particles [10]. Water requirement and carbon content are directly proportional unlike the presence of coarse fly ash particles. Helmuth stated that appropriate
dispersion of fly ash particles on cement grains decreases water amount. This effect is the same as that of water reducers [11].

Tokyay proved that Class C fly ashes may not be as effective as Class F fly ashes in reducing heat rise during hydration due to their relative reactivity [12, 13]. Low lime fly ashes generally reduce the degree of heat rise when used as a cement replacement. High lime fly ashes are usually more reactive than are Class F fly ashes, so they do not essentially cause a decrease in heat evolution. Based on field applications in Canada, 30 % of fly ash replacement have been reported to decrease the heat of hydration [13].

Previous studies showed that for low strength and high strength application, 30-80 % fly ash replacement level can be used [14]. In load-bearing applications, the level of cement replacement ranges from 15 % up to 30 %, the maximum acceptable limit for strength development [15].

Carette and Malhotra investigated the performance of eleven different types and various origins of Canadian fly ashes. Their study consisted of two lignitic, three subbituminous, and six bituminous fly ashes. They stated that, besides the fly ash type, a 20 % fly ash replacement with cement caused lower compressive strength in the early period of hardening [7]. Several studies have been performed to optimize the fly ash level for mortars and concretes in load-bearing elements [16]. Swamy et al. indicated that concrete mixes composed of 30 % Class F fly ash by weight of binder amount could be proportioned to have satisfactorily workable mixes. Additionally, the percentage of water reducer was adjusted to attain the desired workability with a slump value of more than 100 mm for easy placing in structural grade reinforced concretes [17].

For roller-compacted concrete or mass concrete applications, high replacement level of fly ash is usually restricted. However, fly ash level of 40 to 60 % can be used adequately in normal structural concrete [18]. By contrast, it is believed that higher replacement percentages are feasible in low strength and non-structural grade concrete applications, such as in highways and road-bases [16] as well as in low w/c with 50 % ASTM Class F structural grade concrete [7].

For HVFA concrete’s site applications, compressive strength at 28 and 90 days was reported as 35-50 MPa and 50-70 MPa, respectively. Samples obtained from large blocks composed of HVFA concrete attained 110 MPa compressive strength beyond 10 years [19]. Wilbert et al. mentioned that optimum fly ash replacement level should be between 55 % and 60 % for structural grade concrete [7]. Gopalan determined the optimum quantity of fly ash for structural grade concrete applications. Strengths of the mixtures were evaluated at 7 and 28 days. He mentioned that the ideal fly ash replacement level was directly related to the method of mixture proportioning. Additionally, the author stated that evaluation of composite behaviour using “cementing efficiency of fly ash” was unpredictable and the rate of strength gain in concrete was directly related to the “gel/space ratio.” The study proved that a “gel/space ratio” of 0.70 is the optimum for fly ash concrete considering the strength properties [20].

Taniguchi et al. evaluated the performance of HVFA concrete for use in the construction of marine structures. They reported that the strength characteristics of HVFA concrete depended on amount and type of chemical admixture and curing regime. In their study, NaCl was used as a chemical activator, and test results showed higher early strength and excellent rate of strength gain with curing. Additionally, HVFA concrete exhibited good resistance against seawater with respect to volume changes [21].

Cuijuan et al. conducted experiments to examine the effect of the optimum high lime fly ash replacement on concrete strength. The experimental data showed that concrete composed of 25 % fly ash or less was an optimal level to achieve higher strength. When the replacement level increased to 40 %, concrete either increased or attained the equal strength without fly ash concrete for both curing ages of 90 days and 180 days [22].

An experimental study conducted at the University of North Dakota on high calcium fly ash concretes selected ash replacement level of 30 %. As a result, high lime fly ash resulted in higher early strength compared to Class F fly ash [23].
Hooton examined the effect of incorporating high alkaline fly ash in concrete applications. The results showed that the availability of the high amount of alkalis in fly ash does not produce expansive gel and does not contribute to an alkali silicate reaction. The fly ash replacement level of 35% showed lower compressive strength of concrete at 1-day and identical strength beyond 7 days. However, beyond 28-days, higher strengths were recorded [24].

Sivasundaram et al. proportioned several concrete mixtures composed of HVFA (low lime), superplasticizer, and AEA. Blocks with dimensions of 1.52x1.52x1.52 m were manufactured to evaluate the rate of heat rise on the hydration of cementitious materials. The HVFA concrete composed of superplasticizer showed superior performance. The concrete attained higher compressive strength at all testing ages. Based on this research, the samples attained 40 MPa compressive strength at 91-days (w/c ratio of 0.33) and 53 MPa (w/c ratio of 0.28). Based on the field performance evaluation of this concrete, a concrete block with 8.84x7.32x 2.74 m dimensions was also produced under controlled conditions. Thermal cracks were not observed in this study, and strengths were similar to those produced in the laboratory [25]. In another study, Sivasundaram et al. showed that the long-term performance of HVFA concrete was excellent with respect to compressive strength [26].

Naik et al. examined the engineering properties of concrete composed of a high amount of low lime fly ashes obtained from two different sources. Fly ash replacement level was between 0-60% to attain 41 MPa at 28-days. The superplasticizer was used to preserve the consistency of the design mixture groups and adjust the w/c ratio. The compressive and tensile strength of the produced concrete increased with testing age and decreased with fly ash amount. For compressive strength, 30 MPa was measured at 28 days at a 60% fly ash replacement. The study revealed that the concrete containing up to 60% fly ash could be used to meet fresh and hardened requirements for load-bearing applications [27].

Naik et al. prepared three mixture groups for concrete which can be used in paving work. The mixtures comprised 20% and 50% Class C fly ash and the third mix contained 40% Class F fly ash. Total binder amount for three mixture groups was about 270 kg and contained an AEA and superplasticizer. The compressive strength of mixtures containing either 40% low lime fly ash or 50% high lime fly ash had lower compressive and tensile strengths compared to the reference mixture containing 20% high lime fly ash. The HVFA concrete mixes showed similar results with respect to compressive and tensile strengths. The authors stated that for paving applications, concrete could be produced with 40% of the low lime fly ash at a w/c below 0.36. Additionally, concrete containing 50% high lime fly ash showed good performance in paving applications [27].

Langley evaluated the flexural strength of concrete composed of 55% low lime fly ash. The flexural strength varied from 7.2-7.5 MPa (w/c ratio: 0.27) and from 5.6-6.3 MPa (w/c ratio: 0.49) considering the 91-365 days of hardening [28]. Sivasundaram et al. reported that 14 days and 91-days flexural strength values of concretes comprising 58% of total cementitious materials ranged between 4.5 MPa and 5.6 MPa, respectively [26]. Naik et al. reported that the flexural strength of concrete containing HVFA varied from 4.4-7 MPa at 28-days and varied from 4.4-4.9 MPa at 56-days. Additionally, the splitting tensile strength was recorded as 3.5 MPa at 28-days for the medium strength grade HVFA concrete produced at Canada Center for Mineral and Energy Technology (CANMET) [27].

Mather found that cement composed of high C3A content replaced with 30% level can decrease sulfate resistance. Conversely, Mehta, Hooton, and Manz et al. showed that high lime fly ashes may satisfactorily increase the concrete’s sulfate resistance [29].

Wesche and Schubert produced concrete containing 50% fly ash and recorded an increase in sulfate resistance when low sulfate resistance cement was used. The positive contribution of fly ash in sulfates is that it reduced the overall pH level in the pore solution due to reduction of the amount of calcium hydroxide [30-32].

High lime fly ash has been proven its performance, and it is commercially available as a building material used mostly in cement production, various concrete elements, embankments, structural fill, and road sub-bases [33].
Freezing and thawing tests results of masonry units composed of fly ash showed that these units could be expected to perform well in vertical wall construction. For severe lateral exposure, a minimum compressive strength of 21 MPa is recommended [31].

Based on the quality and safety issues, international codes had revised the minimum strength requirements for concrete masonry units and structural grade concrete construction. Block manufacturers suggested that for both light and normal weight units, minimum compressive strength should be 24.5 MPa and 34.5 MPa, respectively [7].

Based on the previous attempts stated above, the fly ash utilization level in the construction sector is still low. This study focused on the HVFA utilization as a partial replacement to cement. Pure cement paste composites were produced. The research also considered the sustainable development and manufacturing of ecological construction materials composed of HVFA.

2. Materials and methodology

OPC, conforming to ASTM C150M-12 standard, was used. The fineness and specific gravity of the cement were 293 m²/kg and 3.09, respectively. High lime fly ash was brought from Soma thermal power plant in Turkey. Water reducer was used in 70FA30C mixture groups. Tap water was used in all stages of the study. The chemical compositions of cement and fly ash are presented in Table 1.

| Chemical (%) | Soma fly ash | Cement |
|--------------|--------------|--------|
| SiO₂         | 41.28        | 18.91  |
| SiO₂ (insoluble) | –        | 0.68   |
| Al₂O₃        | 22.51        | 4.96   |
| Fe₂O₃        | 5.33         | 3.71   |
| CaO          | 20.96        | 62.61  |
| MgO          | 2.05         | 1.72   |
| SO₃          | 1.78         | 2.47   |
| LOI*         | 2.46         | 3.73   |

2.1. Methodology

Four mixture groups composed of a high amount of fly ash with mass ranging from 60-100% were chosen to produce cement paste composites. Casting samples were demoulded 1 day after mixing. The samples were preserved at a controlled condition (T: 24°C and RH: 95%). Physical properties of the composites were evaluated based on a flow table, fresh unit mass, porosity, apparent specific gravity, dry unit mass and water absorption tests. Mechanical characterisation was evaluated by compressive and flexural strength tests. Tests were conducted at 7 and 28 days. Average of the six samples were used for evaluation. The studied mixture groups are presented in Table 2. In Table 2, FA denotes fly ash, C denotes cement by % mass and Adm denotes admixture addition by mass.
Table 2. Mixture Groups of the study.

| Group      | Fly ash (FA) (%) | Cement (%) | Admixture (%) | Water/binder (w/b) |
|------------|------------------|------------|---------------|--------------------|
| 100FA      | 100              | 0          | 0             | 0.41               |
| 80FA20C    | 80               | 20         | 0             | 0.41               |
| 60FA40C    | 60               | 40         | 0             | 0.41               |
| 70FA30C0.6 Adm | 80       | 20        | 0.6           | 0.41               |

3. Results and discussions

Flow table values of the composites are shown in Figure 1. Fresh unit weights (FUW) of composites varied from 17.1 kN/m³ to 18.0 kN/m³. Generally, reduction in the frictional force can improve the fresh fly ash cement paste properties. Opposing charges on the adjacent particles of cement can exert electrostatic attraction. Increasing solid volume by pore-filling mechanisms causes also an increase in the fresh unit weight [34]. Additionally, flowability of the composites improved with increased fly ash replacement level in the paste shown in Figure 1.

The reaction products of fly ash are very effective in pore refinement of large capillary voids, improving the many intrinsic properties of the matrix. Admixture addition most probably adsorbs on the water-cement interface and directly induces the surface tension of water. They begin to disintegrate into their ionic components. This affects the workability and friction among the particles [2].

Water to binder ratio (w/b) had a greater effect on the overall performance of the final composites. The reduction in w/b ratio had a positive effect on water reducer admixture in the mix. When w/b ratios increased, the WRA became ineffective. Degree of the cohesion and the size of the liquid phase caused a significant change in the fresh properties. In Figure 2, the apparent specific gravity of the mixture groups is shown. Apparent specific gravity (ASG) is an important property to evaluate the pore structure of the composite materials. As seen in Figure 2, increased replacement level of fly ash increased the ASG values.
Figure 2. ASG values of mixture groups (7 and 28-days).

Figure 3 shows dry unit mass (DUM) of mixture groups is shown. Based on the DUM values of Soma fly ash mix groups, the laboratory produced composites can adequately be used in the production of aerated composites. DUM value of aerated composites varies from 300-2100 kg/m$^3$, and because of their air trapping capacity, composites are an accepted sound permeable and thermal comfort material commonly used in the production of lightweight wall composites. This can be considered as a perfect condition for the production of marketable lightweight panels and factories as well as residential building materials. Because of their partial reaction, the hydration products become mature. PC pastes result from the advanced crystallization of the hydration products. Thus, soluble chemicals can affect either the “degree of ionization of cement compounds” or the “degree of crystallization of the hydration products.” This influences the setting characteristics of the pure paste composites [35].

A DUM value of the final composites indicates that final composites are in the range of lightweight concrete. The material is a lightweight composite with dry unit weight ranging between 11.9 and 16.5 kN/m$^3$, which is quite lower compared to that of conventional construction materials promising beneficial outcomes in terms of construction costs and earthquake safety [4]. The final product can be used adequately in the production of lightweight aggregates and semi-isolating elements. The mixture proportion of lower mass is particularly beneficial under poor soil conditions.
The water-reducing effect increases with dosages of fly ash. At a higher fly ash replacement level, pore solution occupies the voids between the fly ash particles. The behaviour is controlled by particle packing phenomena. Large pores can only be occupied by hydration products which are also required for the self-healing of cement hydrates or fly ash itself [36]. Figure 4 shows the water absorption (WA) of mixture groups. Water absorption values indicate that mixtures composed of 60% fly ash are adequate for the production of construction material, such as bricks, tiles and paving stone manufacturing. The standard limit for water absorption is nearly 16% for building materials. Although the increases of the amount of fly ash above 60% showed higher standard limits, as shown in Figure 4, it could be possible to decrease the specified limits after longer curing periods (i.e., after 28-days).

![Figure 3. DUM values of mixture groups (7 and 28-days).](image)

![Figure 4. Water Absorption of mixture groups (7 and 28-days).](image)
The decrease in WA values revealed that increased density resulted in the pore refinement. Figure 5 shows the porosity values of mixture groups. Fly ash replacement increases the porosity values.

![Graph showing porosity values of mixture groups](image)

**Figure 5.** Porosity values of mixture groups (7 and 28-days).

As illustrated in Figure 5, the WRA shows less efficiency with fly ash, although the reactivity of available glassy phase is higher to absorb water. “Fly ash particles are spherical in shape” and Class C particles are not easily dispersed through the solution. However, the mixtures composed of WRA decreased the water demand. This might be due to fly ash particles absorbing the molecules of WRA to form “double electrical layer” and retaining the particles away from each other. The effect of surface area, porosity and water content varied little before and after the replacement level. However, the effects reduced gradually with the increase of replacement [37]. The weak phase between the fly ash particles seemed to have decreased considerably, though certain parts had higher porosity. The bond among those two phases may be weak during the early stages of hydration. Formation of stable hydrate products due to modification of unstable regions indicated that bond develops as hydration continues [38].

Figure 6 shows the unconfined compressive strength (UCS) values. The UCS results of mix design groups of Class C fly ash at 28 days showed that the final composites can be classified as C25/C30 concrete strength class for 60FA40C groups. The increase in fly ash amount caused a slight reduction in UCS values. The optimum level for fly ash replacement seems to be 60%.
Figure 6. UCS values of mixture groups (7 and 28-days).

The rate of strength increase based on the cement hydration causes the development of bonds, and continuous hydration can decrease in overall porosity of the composites. The volume of hydration products in cement paste remains nearly constant during the early period. However, the volume of solids within the bulk increases with age and thus causing a reduction in the porosity of the paste. The UCS increases with decreasing porosity of the composites. This improvement in UCS may be due to the development of hydration products that are gradually replaced by liquid between cement particles. The space between the particles decreases and the overall porosity of the paste reduces with ongoing hydration [39]. Considering the pozzolanic activity and hydration, the packing effect is more important for the arrangement of small particles that fill the small pores and contribute to the increase of UCS [30]. Generally, finer particles produce higher compressive strength value compared to the larger ones [40]. It can be concluded that fly ash and cement combinations significantly enhance the composite’s UCS value. In general, the fly ash replacement level (above 50%) reduced the strength of the hardened cement paste at the 7-days. Based on the UCS tests results, composites have adequate strength for civil engineering applications and building construction elements, such as road bases, bricks, tiles, and ceramic.

Figure 7 shows the flexural strength (FS) values of the produced composites. FS and UCS are highly correlated, and the same trend with UCS was observed. The lowest FS values in pure fly ash mix groups are due to higher water requirement of the fly ashes that considerably reduces early and late FS values. For pavements, UCS value is less critical compared with FS values. Adequate curing is essential for fly ash-cement mixes. The rate of hydration is slow and aggressive environments, such as freeze-thaw, sulfate and chloride attack, are very risky for composite’s strength. The fly ash mixes are vulnerable to those attacks, and any expansion and contraction of gel during ion-exchange of pore solution by adsorption of water in pores may reduce FS of the composites. This decrease in FS can be overcome by using chemical admixtures to stabilize the fly ash particles.
4. Conclusions and recommendations

1. The final composites can be used satisfactorily in the manufacturing of aerated composites. DUM values of the laboratory-produced composites vary from 300-2100 kg/m3.

2. The material is a lightweight and sound composite; the unit weight ranges between 11.9–16.5 kN/m3, which is quite lower than those of conventional material of construction.

3. The efficiency of the water reduction in high lime fly ash is low in the absence of water reducers.

4. Most water absorption (WA) values of the HCP composites are higher than that of WA values specified in the related standards. However, the absorption value of the mixture groups composed of 60% fly ash satisfies the standard limits (lower than 16%).

5. The 28 days UCS results of the 60FA40C mix groups show that the final composites can be classified as C25/C30 concrete strength class.

6. FS value of 6.9 to 8.8 is required for vehicular paving applications. The design groups had failed for load-bearing applications.

7. It is recommended to study fly ashes with different fineness values to investigate in more detail the microstructure, freezing-thawing resistance, and abrasion resistance of HVFA cement paste composites.

References
[1] EPA–452/R-03-006 Report 2003 Economic Impact Analysis for the Brick and Structural Clay Products Manufacturing NESHAP: Final Rule, 25 pp.
[2] Aydin E and Arel H Ş 2017 Constr. Build. Mat. 157 96-107
[3] Aydin E and Arel H Ş 2018 Data in Brief 16 321-326.
[4] Aydin E 2009 Fifth International Conference on Construction in the 21st Century (CITC-V) Collaboration and Integration in Engineering, Management and Technology May 20-22, Istanbul, Turkey p.1526-1535.
[5] Bouzoubaa N, Zhang M H and Malhotra V M 2000 *Cement Concrete Res.* **30** 1037-1046.
[6] Bouzoubaa N and Fournier B 2003 *Cement Concrete Res.* **33** 1029-1037.
[7] Naik T R 1992 *Report on CBU-1992-15* 169 pp.
[8] Erdoğan T Y 1997 *Admixtures for Concrete* (Middle East Technical University Press) 188 pp.
[9] Joshi R C 1979 *Proceedings of the Fifth International Fly Ash Utilization Symposium, Atlanta* p. 610-623.
[10] Helmuth R A 1987 (Portland Cement Association) 203-205.
[11] Helmuth R A 1986 *Proceedings of the Second International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Madrid, Spain* (Malhotra V M Ed) *ACI SP-91* 723-740.
[12] Tokyay M 1988 *Cement Concrete Res.* **18** 957-960.
[13] Siddique R and Khan M I 2011 *Supplementary Cementing Materials* (Springer-Verlag Berlin Heidelberg) 288 p.
[14] Aydin E 2017 *Constr. Build. Mater.* **153** p. 393-401.
[15] Ravina D and Mehta P K 1988 *Cement Concrete Res.* **18** 571-583.
[16] Aydin E and Balkis A P 2017 *ASTM J Testing Eval* **45 (6)** 2029-2038
[17] Swamy R N, Sami A R A and Theodorakopoulos D D 1983 *ACI Mat Journal* **1** 414-423.
[18] ACI 318-19 2019 (ACI Publications) 391 pp.
[19] Zhang M H, Bilodeau A and Malhotra V M 1998 *Cement Concrete Res.* **28 (11)** 1555-1569.
[20] Gopalan M K 1991 *Proceedings: Shanghai Ash Utilization Conference, 2 (EPRI Report No. GS-7388)* 59-1 to 59-10.
[21] Taniguchi K, Suzuki T, Shimomura Y, Ohga H and Nagataki S 1989, *Proceedings of the Third CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Supplementary Papers, Trondheim, Norway* pp. 66-91.
[22] Cuijuan S, Loushu G and Haimin W 1986 *Proceeding of the Second International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Madrid, Spain* (Malhotra V M Ed, *ACI Publication SP-91*) 387-412.
[23] Manz O E 1970 *Electric Power Symposium on the Use of Ash, in Particular in Production of Concrete and Prefabricated Construction Elements, Ankara.*
[24] Hooton R D 1986 *Proceedings of the Second International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Madrid, Spain* (Malhotra V M Ed., *1 ACI Publication SP-91*) 333-345.
[25] Sivasundaram V, Carette G G and Malhotra V M 1987 *Proceedings of the Eight International Coal Ash Utilization Symposium 2* (ACAA Washington, D C) 34-1 to 34-13.
[26] Sivasundaram V, Carette G G and Malhotra V M 1989 *Third International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Trondheim, Norway.*
[27] Naik T R, Ramme B W and Tews J H 1991 *Proceedings: Shanghai Ash Utilization Conference 2 (EPRI Report No. GS-7389)* 60-1 to 60-20.
[28] Langley W S 1991 *70th Annual meeting of transportation research board, Washington, D.C.*
[29] Ramyar K 1993 Effects of Turkish Fly Ashes on the Portland Cement Fly Ash Systems *PhD Thesis*, 208 pp.
[30] Wesche K 1991 *Fly Ash in Concrete: Properties and Performance* (Chapman and Hall, Newyork) 256 pp.
[31] Mather K 1982 *George Verbeck Symposium on Sulfate Resistance of Concrete (SP-77, ACI, Detroit)* 63-74.
[32] Tütünli F 2000 The Utilization of Fly Ash in Manufacturing of Building Bricks. *M.Sc. Thesis.*
[33] Aydin E 2009 *International Conference on Concrete Repair, Rehabilitation and Retrofitting, Cape Town, South Africa* (London: CRC Press) 109-115.
[34] Alshamsi A M, Alhosani K I and Yousri K M 1997 *Magazine of Concrete Research* **49 (179)** 111-115.
[35] Mehta P K and Monteiro P J M 2001 *Microstructure, Properties and Materials*, 2nd ed. 239 p.
[36] Xu A and Sarkar S L 1994 *J. Mater. Civil Eng.* 6 (1) 117-136.

[37] Sun W Handong Y Binggen Z 2003 *Cement Concrete Res.* 2301 1-7.

[38] Zhang M H 1995 *Cement Concrete Res.* 25 (6) 1165-1178.

[39] Hewlett P C 1988 *Lea’s Chemistry of Cement and Concrete* (John Wiley and Sons Inc, Newyork) 1053 p.

[40] Aydin E 2019 *10th international concrete conference, May 2-4, Bursa, Turkey* 419-429.