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Durability performance of concrete incorporating Class F and Class C fly ashes

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ABSTRACT

This paper presents an experimental study on the durability properties of concretes containing Turkish Class C and Class F fly ashes. A total of 39 mixtures with different mix designs were prepared. In order to characterize the concrete quality, compressive strength of the specimens were obtained. After that, the mixtures containing Class F and Class C fly ashes which had similar compressive strength values to control mixtures at 28 d for each series were used for durability tests. The durability performance of the concretes was assessed from measurements of rapid chloride ion permeability, sorptivity and freezing–thawing resistance tests. The degree of freezing–thawing resistance was evaluated using change of weight, ultrasonic pulse velocity (UPV) and flexural strength after 300 cycles. The test results indicated that Class C fly ash showed higher compressive strength than Class F fly ash. The addition of fly ash improved the rapid chloride ion permeability and sorptivity of concrete. There was a notable reduction in the UPV after the specimens are subjected to freezing–thawing cycles. The amounts of flexural strength loss have been measured in the range of 5.38–29.83%. The use of Class C and Class F fly ashes positively affected freezing–thawing resistance of concretes.

1. Introduction

Concrete is the most important element of the construction industry. In recent years, since durability is one of the critical issues to construct reinforced concrete structures with long service life and develop construction technologies due to some economical and environmental reasons, it is important to produce well-designed concrete as a durable construction material [1]. However, large amounts of cement are used in concrete production. Cement is the most cost- and energy-intensive component of concrete. Three billion tons of raw materials are used in each year for cement production in the world [2] and, cement manufacturing is responsible for about 2.5% of total worldwide CO_2 emissions from industrial sources [3,4]. The use of additional cementitious materials due to technical, economic and environmental considerations has become very common in modern concrete construction. The use of these materials in concrete is increasing because they result in lower cost of construction and improve some physical, mechanical and durability properties of concrete in aggressive environments [5]. Mineral admixtures such as silica fume, ground granulated blast furnace slag and fly ash (FA) generally improve the engineering properties of concrete when they are used as a mineral additive or partial replacement of cement [6,7]. Among these mineral admixtures, FA has been used in concrete production for over 52 years in the world. It was used in mass, conventional and high performance concrete to improve the workability, to reduce the heat of hydration and thermal cracking at early ages, and to improve the mechanical and durability properties especially at later ages [8]. The main useful effect of FA in concrete consists of three aspects, often called pozzolanic effect, micro aggregate effect and morphologic effect. The pozzolanic effect is the main effect of FA, which states that the unfixed Al_2O_3 and SiO_2 in FA can be activated by $Ca(OH)_2$ product of cement hydration and produce more hydrated gel. Since the gel produced from pozzolanic action can fill in the capillary in concrete, it effectively conduces to concrete strength. The micro aggregate effect of FA states the microbeads in FA can disperse well in concrete and combine firmly with gel produced in cement hydration, and thus promote concrete density. The morphologic effect states that there are many microbeads in FA working as "lubricating balls" when incorporated in fresh concrete; hence it benefits the fluidity [9].

Fly ash is widely used in blended cements, and is a by-product of coal-fired electric power plants [10]. Two general classes of fly ash can be defined: low-calcium fly ash (ASTM Class F) produced by burning anthracite or bituminous coal; and high-calcium fly ash (ASTM Class C) produced by burning lignite or sub-bituminous coal [11]. Class F is categorized as a normal pozzolan, a material consisting of silicate glass, modified with aluminum and iron. Class F requires $Ca(OH)_2$ to form strength-developing products (pozzolanic reactivity), and therefore is used in combination with Portland cement, which produces $Ca(OH)_2$ during its hydration. It lowers the heat of hydration and improves the durability when used in concrete as a cement replacement. It also contributes to concrete

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strength by pozzolanic and filler effects [12]. The current annual worldwide production of coal ash is estimated about 700 million tones of which at least 70% is fly ash. There are 11 thermal power plants actively working in Turkey but Class F fly ash is obtained only from Catalagzi Thermal Power Plant, FA of all other plants is Class C. As for today, the annual fly ash production is about 20 million tones which is more than the rest of all industrial wastes in Turkey. Although FA is a valuable mineral admixture for blended Portland cement and concrete, only about 4% of the total available FA is used for this purpose in Turkey [13]. In particular, due to the energy demand, the production rate of FA is expected to increase in the future [14].

Durability is a key function for materials which are used in severe environments [15,16]. In cold environments, the freezing and thawing durability is especially important for a porous brittle material such as concrete when it is subjected to lower temperatures [17]. Frost damage, a progressive deterioration which starts from surface separation or scaling and ends up with complete collapse, is a major concern when concrete is used in colder regions. The deterioration proceeds as freezing–thawing cycles are repeated, and the material gradually loses its stiffness and strength. In addition, increasing irreversible expansion is induced. So, the freezing and thawing action could be looked upon as a very complex fatigue process. Now there are increasing needs for concrete to be used for the shortage of very cold substances. So, a rational evaluation of deterioration is essential in designing more reliable structures and minimizing possible damage [18].

Water is the main cause of the degradation of building materials. It penetrates into porous media, transports harmful substances and freezes inside. When a homogeneous porous material has a constant hydraulic potential at wet front, liquid can mount to considerable heights due to the capillary absorption. If evaporation takes place, equilibrium between capillary absorption and evaporation is reached at a certain height [19]. For this reason, in technical practice heights of approximately 1 m above ground level are considered in moisture degradation of building constructions [20]. With the deterioration of existing structures, durability of concrete is of great concern [17]. For structures in cold areas, freezing–thawing resistance of concrete is especially important. Concrete exposed to temperature cycles, where water freezes to ice and ice melts to water in winter, is deteriorated due to freezing and thawing. As the temperature lowered, the water held in the capillary pores freezes and expansion of the void occurs. Thus, repeated cycles of freezing and thawing deteriorate concrete rapidly [21,22].

The objective of this study is to investigate the effect of the use of Class C and Class F fly ashes as partial replacement of cement in various percentages, on concrete properties such as some mechanical and durability characteristics of the concrete. Several properties related to durability were determined such as chloride ion permeability resistance, sorptivity and particular attention was put on the resistance of the concrete mixes to the freezing and thawing cycles based on ASTM C 666.

2. Experimental procedures

2.1. Materials

In this study, CEM I 42.5 R Portland cement, Class C and Class F fly ashes were used as binding materials. Their chemical compositions and properties are shown in Table 1. Both Class C and Class F fly ashes were obtained from power plants in Turkey. Specific gravity of the cement used was 3.12 g/cm^3. Initial and final setting times of the cement were 210 and 265 min, respectively. Crushed limestone aggregates with a maximum size of 16 mm were used as coarse aggregates. The specific gravity and water absorption of the crushed limestone aggregate was 2.70% and 0.31% respectively. Ordinary river sand with specific gravity of 2.61 and water absorption of 1.59% was also employed. A uniform grading of aggregate mixture was prepared. The fineness modulus of the mixture is 4.09. Volume percentages of aggregates were kept constant in all mixtures. The particle size distributions of cement, Class C and Class F fly ashes were obtained by a laser scattering technique and are presented in Fig. 1.

Table 1
Properties of Portland cement and fly ashes.

Component (%)	Cement	Class C fly ash	Class F fly ash
Chemical composition (%)			
SiO_2	20.63	46.38	58.58
Fe_2O_3	3.41	8.26	6.97
Al_2O_3	4.71	13.9	23.4
CaO	63.64	15.1	1.55
MgO	1.24	6.68	2.76
SO_3	2.98	4.26	0.45
Cl^-	0.04	0.06	0.03
Loss Ignition	1.25	0.22	0.2
K_2O	0.91	2.78	4.11
Na_2O	0.23	2.13	0.46
Free CaO	1.1	0.15	0.1
Physical properties			
Specific gravity	3.12	1.84	2.34
Blaine (cm^2/g)	3545	2850	3350

2.2. Mixture proportions

Three different cement dosages were used (260, 320, 400 kg/m^3) two different ratios (10% and 17%) of reduced cement from the control concretes and three different ratios (depending on cement reduction ratio) of fly ash were added into the mixtures. The workability values of mixtures were similar to each other with a slump of 140–170 mm. The main variable in the mixtures was the cement, fly ash and the water content. The mixture proportions of the concretes are shown in Tables 2 and 3. The raw materials of concrete were put in a forced mixer at the same time and were mixed for 3 min. The workability of fresh concrete including slump was measured immediately after the mixing was completed. The results are listed in Tables 2 and 3. Slump, density and the air content of fresh concretes were obtained. The mixtures were cast into test specimens in mould by vibration. 36 series of concretes containing Class C and Class F fly ashes and three series of control mixtures were produced in order to investigate compressive strength properties of concretes. After that, the mixtures containing Class F and Class C fly ashes which had similar compressive strength values to control mixtures at 28 d for each series were used for durability tests. However, the selected mixtures for durability tests determined from two results had similar compressive strength values to control mixtures at 28 d for each cement content and fly ash type. One of them was the mixture had 10% or 17% cement replacement rate (reduced cement from the control concretes) and the other one was the mixture had fly ash was added and this situation caused an increase in binder content (depending on cement reduction ratio).

2.3. Casting, testing and curing of specimens

Compressive strength test was made on 150 mm cube specimens. All specimens were demoulded in a controlled chamber at 20 ± 2 °C after 1 d of casting, and cured in lime-saturated water at 20 °C and 65% RH. Compressive strength test was

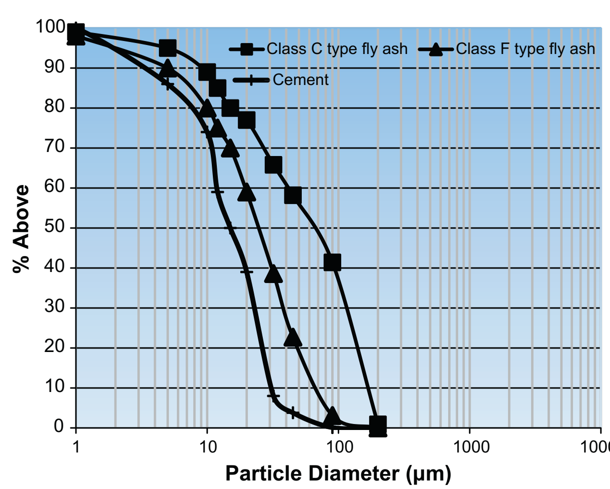

Fig. 1. The particle size distributions of fly ashes and Portland cement.