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Adverse effects of high temperatures and freeze-thaw cycles on properties of HFRHSCs containing silica fume and metakaolin

Murat Çiflikli [a], Mustafa Sarıdemir [b,*], Faruk Soysat [b]

[a] Department of Geology Engineering, Niğde Ömer Halisdemir University, 51240 Niğde, Turkey
[b] Department of Civil Engineering, Niğde Ömer Halisdemir University, 51240 Niğde, Turkey

HIGHLIGHTS

- Adverse effects of HTs and F-T cycles on the properties of HFRHSCs were investigated.
- Changes in the U_{pv}, f_c, $f_{ct,fl}$ and $f_{ct,sp}$ values of concretes exposed to adverse effects were evaluated.
- Changes in the matrix, interface zone and aggregate of concretes exposed to adverse effects were examined.
- Results have revealed that SF and SF + MK have important effects on the properties of concretes.
- The properties of concretes with hybrid fibers from HTs have affected more than that of concretes without fibers.

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ABSTRACT

Adverse effects of high temperatures (HTs) and freeze-thaw (F-T) cycles on the properties of hybrid fibers reinforced high strength concretes (HFRHSCs) containing silica fume (SF) and silica fume + metakaolin (SF + MK) were investigated in this study. Concrete mixtures without and with hybrid fibers (HFs) up to 20% replacement by the weight of Portland cement (PC) with SF and SF + MK were made with the water-binder ratio of 0.25. Experimental studies were conducted on the specimens prepared from these mixtures to determine the ultrasound pulse velocity (U_{pv}), compressive strength (f_c), flexural strength ($f_{ct,fl}$) and splitting tensile strength ($f_{ct,sp}$) values of concretes without and with HFs exposed to ambient temperature (AT) and HTs. Moreover, the experimental studies were performed to determine the U_{pv} and f_c values of concretes exposed to F-T cycles. Microstructure analyses were also conducted on the specimens to examine the changes in the matrix, interface zone and aggregate of concretes without HFs exposed to AT, HTs and F-T cycles. Experimental results have revealed that replacement ratios of SF and SF + MK have important effects on the properties of concretes without and with HFs. The experimental results have also shown that the f_c, $f_{ct,fl}$ and $f_{ct,sp}$ values of the concretes with HFs are higher than the concretes without HFs. The U_{pv}, f_c, $f_{ct,fl}$ and $f_{ct,sp}$ values of the concretes with HFs have been affected more than that of the concretes without HFs due to the adverse effects of HTs.

1. Introduction

For nearly twenty-five years, pozzolanic materials, such as fly ash, SF, MK and ground granulated blast-furnace slag, have been employed as partial substitution materials of PC in concrete mixtures and many specific types of concretes. High performance concrete, self-compacting concrete, high strength concrete, reactive-powder concrete, lightweight concrete, roller compacted concrete, etc. are the types of concrete in which these materials are used. Generally, these materials are employed in order to improve the microstructural and mechanical properties of concretes. Besides, these materials are employed to improve the durability properties of concrete such as freeze-thaw [1,2], sulfate attack [2–4], acid attack [5], alkali-aggregate reaction [6] and corrosion [7]. These materials contribute to the improvement of the above properties producing additional calcium-silicate-hydrate (C-S-H) gels by reacting with calcium hydroxide ($Ca(OH)_2$) that is a comparatively weak product of cement hydration [8–12]. Moreover, improvement of these properties is also achieved by decreasing the porosity and pore size dispersion in the microstructure due to the filling effect of these materials [12–14]. Besides, the use of these materials as replacement materials of cement in concrete mixtures provides a positive contribution to the environment because of

* Corresponding author.
E-mail address: msdemir@nigde.edu.tr (M. Sarıdemir).

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diminishing CO_2 emission to the atmosphere by reducing the use of cement [11,15].

SF known as one of the artificial pozzolans is a by-product of ferrosilicon and silicon metal industries [2,16]. MK known as one of the natural pozzolans is manufactured by calcining of natural kaolinite clay at a HT range of about 500–950 °C [2,9,11,12]. Especially, the use of these pozzolans has an important place in the production of high strength and durability concretes because of the remarkable improvements on the interface zone of the aggregate with the cement paste. In this case, it shows that the filling effects of SF and MK are more dominant than its pozzolanic effect [16,17]. Because the SF and MK are made up of ultra-fine particles, they make this zone more intense and thus, increase the bond strength between the cement paste and aggregate [17,18]. Hence, they improve the mechanical and durability properties of concretes at the early ages [16]. The strong interface created by the SF and MK increases the stiffness of concrete; therefore, the concrete shows more brittle behaviour [16,19–22]. Many fiber types in different sizes and shapes are used in high strength concrete mixtures containing SF and MK to obtain ductile behavior. Generally, these fiber types are produced from steel, glass, polypropylene and some natural materials [16]. The use of fibers in the different sizes and shapes in concrete mixtures can also improve the other properties of concrete like flexural toughness, modulus of elasticity, durability, f_c, $f_{ct,fl}$, $f_{ct,sp}$, impact and shear strengths [23–25]. Commonly, the type, amount, size and geometry of fibers are influential on the improvement of these properties [25].

Concrete and reinforced concrete structures may be exposed to adverse influences such as fire, HT, F-T, dynamic loads, wearing and chemical medium during service life [26,27]. Mechanical and durability properties of concretes exposed to these type influences have great importance with regard to the serviceability and safety of structures. Especially, although it is known that concrete is a fire-resistant construction material when compared with other construction materials, important changes in its physical properties and chemical composition take place when exposed to HTs [28]. These changes depend on the duration of the exposure to HT, the maximum temperature reached, the rate of heating and the rate of cooling [29]. The type of concrete and the humidity content of concrete also have a great influence on these changes [30]. The influences of these changes in the concretes and reinforced concrete structures are in the form of micro and macro cracking, discoloration, spalling, increase in pores, oxidation and dehydration of $Ca(OH)_2$, C-S-H gels and other cementitious products [29,31], and they adversely affect the microstructural, durability and mechanical properties of concrete. If the concrete is exposed to temperatures up to about 200 °C, the structure of the ettringite decomposes [32], free water evaporates in the concrete, and no significant change is observed in the mechanical and physical properties of concrete. However, if the rate of heating, which causes high vapor pressure, is rapid, micro-cracks occur in the concrete [33]. If the concrete is exposed to temperatures between about 200 and 400 °C, interlayer and combined water in the $Ca(OH)_2$, C-S-H and calcium sulfo-aluminate hydrate gels evaporate, and changes begin to be observed in the mechanical and physical properties of concrete [34]. If the concrete is exposed to temperatures between about 350 and 550 °C, the $Ca(OH)_2$ decomposes to calcium oxide and water, and C-S-H gels entirely dehydrate at these temperatures and decompose at the temperature above 700 °C. The physical, microstructural and mechanical properties of concrete begin to deteriorate at temperatures above 400 °C, but the deterioration rate differs by the properties and type of aggregate forming 70–80% of the concrete mixture by volume [35,36]. When the concrete is exposed to HT, the volumes of the aggregates increase, and cause the pressure of the wrapping around matrix [37]. The thermal properties of aggregates directly affect the thermal conductivity of concrete. Because of diversities in the microstructure properties, porosity and mineralogical compositions, different types of aggregates show various thermal conductivities [36,38]. While the deteriorations and cracks approximately emerge at temperatures 500 °C in the silica-containing aggregates, they approximately emerge at temperature 700 °C in the carbonate-containing aggregates [39,40]. The above explanations show that the weakest components of concrete exposed to HTs are the matrix and silica-containing aggregates.

Several experimental studies have shown that the HTs negatively affect the physical, microstructural and mechanical properties of concrete. Düğenci et al. [26] investigated the effect of HTs on the mechanical properties of steel fiber reinforced concretes. They stated that the use of steel fiber (STF) in the concrete mixtures depending on the HTs (900, 1000, 1100 and 1200 °C) adversely affected the f_c and modulus of elasticity values. Wu and Wu [28] studied the f_c and F-T resistance of ordinary concrete after the HTs (100, 200, 300, 400, 500, and 600 °C). They stated that the f_c values of concrete specimens exposed to F-T cycles after the HT gradually decreased, as the temperature, to which the concretes were exposed to, increased. Ergün et al. [33] investigated the effect of cement dosage on the U_{pv}, f_c and $f_{ct,fl}$ values of concretes exposed to HTs (100, 200, 400, 600 and 800 °C). They stated that the cement dosages had no significant effect on the decrease in the U_{pv}, f_c and $f_{ct,fl}$ values of concretes exposed to HTs. In the study, it was stated that the decreases in the U_{pv}, f_c and $f_{ct,fl}$ values of concretes were very low at temperatures up to 200 °C and the great decreases in these values started after 400 °C. The f_c and pore structure of high performance concretes exposed to HT up to 800 °C were investigated by Chan et al. [33]. They stated that the decrease in the f_c values of high performance concretes containing SF and fly ash with STF or Polymer fiber exposed to HT up to 800 °C was more sharply than that of conventional concrete.

The effects of pozzolanic materials on the properties of high strength concretes were researched by many investigators [9–12,14,17,19,25]. On the other hand, in the literature there were almost no studies investigating the effects of SF and SF + MK on the mechanical properties and microstructure analyses of HFRHSCs exposed to AT, HTs and F-T cycles. Therefore, the effects of SF and SF + MK on the U_{pv}, f_c, $f_{ct,fl}$ and $f_{ct,sp}$ values of concretes without and with HFs exposed to AT and HTs, and the effects of SF and SF + MK on the U_{pv} and f_c values of concretes without and with HFs exposed to F-T cycles were researched in this study. Additionally, the changes in the matrix, interface zone and aggregate of concretes without HFs exposed to AT (25 °C), HTs (300, 400 and 500 °C) and F-T cycles were examined by using polarized light microscope (PLM), scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) spot analyses.

2. Experimental methods

2.1. Materials

An ordinary PC (CEM I 42.5R) was employed to manufacture the high strength concrete mixtures containing SF and SF + MK without and with HFs. The employed SF and MK as pozzolanic materials in the mixtures are shown in Fig. 1. The chemical, physical and mechanical properties of ordinary PC and pozzolanic materials are given in Table 1. Aggregates employed in the high strength concrete mixtures were natural sand (NS), crushed limestone-I (CL-I) and crushed limestone-II (CL-II). Sieve analysis, physical properties and mixing ratios of these aggregates are shown in Table 2. In the types shown in Fig. 1, the commercially available hook ended STF and polypropylene fiber (PF) with length/aspect ratios of 35/47 and 12/923 called as the HFs were used to produce the HFRHSCs. The properties of HFs are shown in Table 3. Polycarboxylic ether based polymer type superplasticizer (SP) (Glenium 51) was employed as high range water reducing admixture to regulate the workability of concrete mixtures. Tap water obtained from city network was employed in the concrete mixtures and curing.