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Elevated Temperature Resistance of Mortars Including Ground Granulated Blast Furnace Slag, Fly Ash and Silica Fume

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ABSTRACT

In the current study, elevated heat resistance of the mortars including 15% fly ash, ground granulated blast furnace slag and silica fume is investigated. Fly ash, ground granulated blast furnace slag and silica fume are replaced with cement past by weight in the prepared mortar samples. The prepared samples are kept in a furnace for 2 hours at 400 °C and 800 °C to find out effect of elevated temperature on compressive strength of the mortars. Compressive strength before and after heat exposure are measured in terms of evaluating elevated heat resistance. Control sample that does not contain any admixture, mortar including fly ash, mortar including ground granulated blast furnace slag and mortar including silica fume has 30.81 MPa, 33.62 MPa, 43.91 MPa and 51.83 MPa compressive strength before heat exposure, respectively. Compressive strength of the same samples after 400 °C and 800 °C heat exposure are 25.64 MPa and 8.12 MPa, 28.91 MPa and 11.56 MPa, 34.37 MPa and 15.21 MPa and 39.78 MPa and 21.85 MPa, respectively. The alteration of heat resistance of the mortars with fly ash, ground granulated blast furnace slag and silica fume is attributed to puzzoulanic behavior of the used materials. These materials react with $Ca(OH)_2$ in cement and produce extra tobermorite gel (CSH phase) that provides extra durability to the composite.

Öğütülmüş Yüksek Fırın Cürufu, Uçucu Kül ve Silika Dumanı İçeren Harçların Yüksek Sıcaklık Direnci

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ÖZ

Bu çalışmada, %15 oranda uçucu kül, öğütülmüş yüksek fırın cürufu ve silis dumanı içeren harçların yüksek sıcaklığa karşı dirençleri araştırılmıştır. Hazırlanan harç numunelerinde uçucu kül, öğütülmüş yüksek fırın cürufu ve silis dumanı ağırlıkça çimento ile yer değiştirilmiştir. Yüksek sıcaklıkların harç basınç dayanımlarına etkisini bulmak için üretilen numuneler 400 °C ve 800 °C'de 2 saat süreyle etüvde tutulmuştur. Harç numunelerinin yüksek sıcaklıklara maruz kalmadan önceki ve sonraki basınç dayanımları, harçların yüksek sıcaklık dirençlerinin değerlendirilmesi için ölçülmüştür. Herhangi bir katkı maddesi içermeyen harç, uçucu kül içeren harç, öğütülmüş yüksek fırın cürufu içeren harç ve silis dumanı içeren harç, ısıya maruz kalmadan önce sırasıyla 30.81 MPa, 33.62 MPa, 43.91 MPa ve 51.83 MPa basınç dayanımlarına sahiptirler. Aynı numunelerin 400 °C ve 800 °C sıcaklığa maruz kaldıktan sonraki basınç dayanımları sırasıyla 25.64 MPa ve 8.12 MPa, 28.91 MPa ve 11.56 MPa, 34.37 MPa ve 15.21 MPa ve 39.78 MPa ve 21.85 MPa'dır. Uçucu kül, öğütülmüş yüksek fırın cürufu ve silis dumanı içeren harçların ısıl direncinin değişmesi, kullanılan malzemelerin puzzulanik davranışına bağlanmaktadır. Bu malzemeler çimentoda $Ca(OH)_2$ ile reaksiyona girer ve kompozite ekstra dayanıklılık sağlayan ekstra tobermorit jeli (CSH fazı) üretir.

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Introduction

Cement is one of the most commonly used construction materials in all over the world (Çağlar et al., 2020). Cement based materials are non-flammable and offer important safety advantages over plastic and wood that are used as construction and building materials. Cement based materials also protects rebar in the reinforced structures. The cement based material covers the rebar and protect the material from environmental and chemical events (Erşan et al., 2008). However, exposure of high temperature causes damages in the cement-based structures. Protection of the cementitious composite is limited by exposure time, temperature etc.

Cementitious composites might be subjected to elevated temperatures that damage the structural properties of materials (Zhou et al., 2020). Fire, thermal shock and industrial applications are some of the cases that cementitious composites expose to high temperatures. In most cases high temperature causes deteriorations in the material due to physical and chemical changes that occur in cementitious composites.

According to literature, cement based composites subjected to elevated temperature up to 300 °C are not affected significantly since the elevated temperature could improve or fasten hydration reactions of cement (Setayesh et al., 2017). However, temperature between 350-550 °C causes strength loose in the material since that temperature range results decomposition of calcium hydrate (CH) into lime (Husem, 2006) and water and further elevated temperature range (700-900 °C) results decomposition of calcium-silica-hydrate gels (C-S-H) (Liu et al., 2019).

Elevated temperature not only affects chemical stability of the cementitious composite but also affect physical stability. Due to different thermal strain behavior of the materials in the cementitious composites cracks are formed with exposure of elevated temperature. Cracks formed as a result of mismatched thermal strains also causes strength loose in the material.

In recent years there have been many researches relating high temperature resistance of cementitious composites. For example, Akbar and Liew (2020) investigated effect of recycled carbon fiber on microstructure and mechanical properties of cement-based composites at elevated temperature. Zemri and Bouiadjra (2020) compared mechanical and physical performance of mortar including ordinary Portland cement and slag cement at elevated temperature. Ming et al. (2020) investigated mechanical and microstructure properties of cement blends with fly ash and aragonite calcium carbonate whiskers. Benli et al. (2020) investigated mechanical performance of self-compacting cementitious composites that contain vermiculite at elevated temperature. AzariJafari et.al investigated binary and tenary blended cement (fly ash, silica fume, natural zeolite, and metakaolin) against elevated temperature (Azari Jafari et al., 2019). Lubloy et al. (2017) investigated fire resistance of Portland-pozzolana or Portland-fly ash cement. Qu et al. (2020) studied elevated temperature resistance of alkali activated ground granulated blast furnace slag (GGBFS) and fly ash based geopolymer mortars. More studies could be found by reading ref (Poon et al., 2001b, 2001a; Kodur and Sultan, 2003; Poon et al., 2003; Aydin and Baradan, 2007; Biolzi et al., 2008; Demirel and Keleştemur, 2010; Kong and Sanjayan, 2010; Cree et al., 2013; Hager, 2013; Khaliq and Kodur, 2013; Nadeem et al., 2013, Khaliq and Khan, 2015; Ma et al., 2015; Ahn et al., 2016; Khaliq and Taimur, 2018; Memon et al., 2019).

In the current paper, physical and mechanical properties of mortars containing GGBFS, fly ash (FA) and silica fume (SF) as replacement of ordinary Portland cement (OPC) at elevated temperature are investigated. The objective of this study is to reveal mechanical and physical properties of mortar including the most available and used puzzolanic admixtures by exposing 400-800 °C heat for 2-hour time duration.

Material and Method

Ordinary Portland cement (CEM I 42.5 R) is used to produce all mortar samples. GGBFS (Iskenderun Iron and Steel Inc., Hatay, Turkey), FA (Afsin-Elbistan Thermal Power Plant, Kahramanmaras, Turkey) and SF (Eti Electrometallurgy Inc., Antalya, Turkey) are incorporated at a single amount of 15% wt partially substituting ordinary Portland cement. Since mineral additives are generally used between 10% and 50% of the cement weight (Puzolanik Maddeler-Panora Makine A.Ş., 2021), in this study, the mineral additive ratio is chosen as 15%, which provides this range. Chemical composition of the GGBFS, FA and SF used are given in Table 1. Calcareous based crushed fine aggregate with maximum grain size of 4 mm and 2.72 specific gravity is used to produce mortar samples. Polycarboxylate ether-based superplasticizer (SP) (Glenium sky 608, BASF) is used (if required) to reach desired workability.

Table 1. Chemical composition of the GGBFS, FA and SF

Chemical composition	**FA (%)**	**GGBFS (%)**	**SF (%)**
CaO	15.70	36.09	0.45
SiO_2	46.97	37.55	92.04
Al_2O_3	11.86	10.55	0.71
Fe_2O_3	7.98	0.28	1.31
MgO	7.01	8.48	–
SO_3	3.47	2.95	0,41
K_2O	3.23	1.07	1.52
Na_2O	2.33	0.24	0.45
Loss on ignition	0.45	2.29	3.11

Binder: Aggregate:Water ratio is kept constant as 1:2.75:0.485 for all mortar samples. Mixture proportions are prepared in accordance with ASTM C-109 (ASTM Standard, 2003). Mix design of the prepared samples is given in Table 2. Dry ingredients are mixed in pan type mortar mixer for 2 min then water is added to the mixture of the binder and aggregate. The mixing procedure is continued until observing homogenous mixture. The fresh mortar that produced after mixing the ingredients are poured into prismatic molds having 40 mm X 40 mm X 160 mm. Molded samples are kept in laboratory environment for 24 hours and mortar samples removed from the molds. After that the mortars are kept in a water tank for additional 27 days.

Table 2. Mix design of the mortars

Sample	**Cement (wt%)**	**FA (wt%)**	**GGBFS (wt%)**	**SF (wt%)**	**Water (wt%)**	**SP (wt%)**
Control	100	-	-	-	100	-
15%FA	85	15	-	-	100	-
15%GGBFS	85	-	15	-	100	-
15%SF	85	-	-	15	100	1

Flexural tensile strength test

Prismatic mortar specimens of size 40 mm X 40 mm X 160 mm are used for flexural tensile strength test at 28 days of water curing. ASTM C348 standards are fallowed during the flexural tensile strength test (ASTM C348-20, 1999). Fallowing formula is used to determine flexural tensile strength value of the mortars. Mean value of the three samples is presented as a result.

$$\sigma = \frac{3Pl}{2bd^2}$$

(1)

Where σ, P, l, b and d are flexural tensile strength, load, span length which is 100 mm, width which is 40 mm and thickness which is 40 mm, respectively.

Compressive strength test

Samples broken into two portions after applying flexural tensile strength test are used for compressive strength test at 28 day of water curing and after exposure of elevated temperature. ASTM 349 standards are followed during compressive strength test (ASTM Standard, 2018). Fallowing formula is used to determine compressive strength value of the mortars. Mean value of the six samples is presented as a result.

$$\sigma = \frac{P}{A}$$

(2)

Where σ, P and A are compressive strength, load and area of the samples load is applied (40 mm X 40 mm), respectively.

Elevated temperature resistance test

Samples broken into two portions after applying flexural tensile strength test are used for elevated temperature resistance test. 28-day water cured samples kept in an oven at 50 °C until observing no change in mas of the specimen. Aim of that procedure is to evaporate free water in the specimens before starting the elevated heat resistance test. After evaporating the free water inside the specimens, the mortar samples are exposed to 400 and 800 °C heat for 2 hours in an oven that temperature inside it increase 5°C/min. It is reported in the literature that the critical temperature range for the loss of compressive strength is 400–800 °C (Chan et al., 1999). For this reason, temperatures of 400 and 800 °C are chosen for the current study. Heat inside the oven starts at 25°C and stays constant at the desired temperature. Specimens are kept inside the oven for 2 hours after the oven reaches the desired temperatures. Specimens are cooled down by switching off the oven. Compressive strengths of the cooled samples are determined to find out elevated heat resistance of the samples.

Results and Discussion

Flexural tensile strength, compressive strength and elevated temperature resistance of mortar samples including 15 % GGBFS, FA and SF as a partial replacement of OPC are presented in this section of the paper. Effect of GGBFS, FA and SF inclusion on the mechanical properties of the mortar is investigated.

Figure 1 shows flexural tensile strength test results of mortar samples including FA, GGBFS, SF and control sample that does not include any additional materials. The control sample has 8.58 MPa flexural tensile strength value while mortar samples with 15% FA, GGBFS and SF have 8.67 MPa, 8.84 MPa and 9.39 MPa flexural tensile strengths, respectively. The highest flexural tensile strength value obtained with the mortar sample including SF while the lowest strength value observed in the control sample. Regardless of the doped material, the flexural tensile strengths of the mortar samples increased with inclusion of FA, GGBFS an SF to the mortar. The strength development in the mortars with doping FA, GGBFS and SF is attributed to the puzzoulanic behavior of the doped materials (Guo et al., 2020; Nedunuri et al., 2020; Zhao et al., 2018).

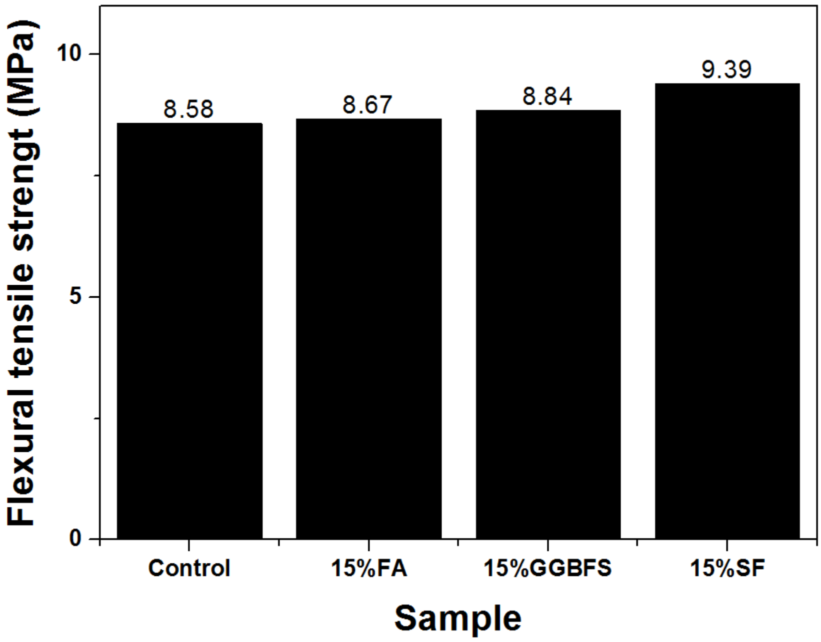

Figure 1. Flexural tensile strength results of mortar samples with different inclusions

Figure 2 shows compressive strength test results of 28-day mortar samples with and without doping materials that are FA, GGBFS and SF. It is seen that among the mortar samples the one with SF has the highest compressive strength value while the control sample that does not contain doping material performed the lowest strength value. The control sample has 30.81 MPa compressive strength value while mortar samples with 15% FA, GGBFS and SF have 33.62 MPA, 43.91 MPA and 51.83 MPa compressive strengths, respectively. It is thought that the doping materials resulted compressive strength development because of providing extra Calcium-Silicate-Hydrate gels to the hydration mechanism by reacting calcium hydrates in the hydration reactions (Cuesta et al., 2021; Jia et al., 2019; Wang et al., 2020). In addition to that SF has the finest particle size compared to the FA and GGBFS. As SF is more reactive then the FA and GGBFS, it has superior effect on compressive strength development of the mortar.

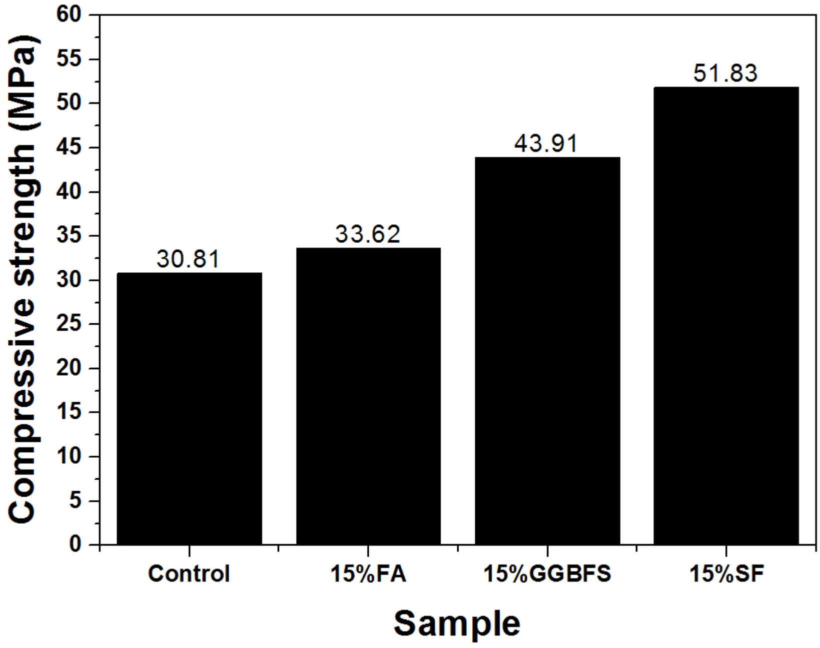

Figure 2. Compressive strength results of mortar samples with different inclusions

Figure 3 shows compressive strength test results of mortar samples rested at room temperature and samples exposed to 400 °C and 800 °C heat for 2 hours in an oven. Heat exposed samples were tested after cooling down. It is seen in the figure that compressive strength values of the mortar samples decrease with elevating the exposure temperature regardless to the doping type. Increasing the exposure heat from 23°C to 400 °C and 800 °C results 17% and 74% strength decrease in control sample, 14% and 66% strength decrease in mortar sample with 15% FA, 21% and 65% strength decrease in mortar sample with 15% GGBFS and 23% and 58% strength decrease in mortar sample with 15% SF. Mortar sample with 15% SF has superior compressive strength value before and after exposure of 400 °C and 800 °C heat. It has the highest compressive strength at room temperature (before heat exposure) and after elevated heat temperature among the other doped mortar samples. This behavior is parallel to the 28-day compressive strength behavior of the mortar samples. The higher the compressive strength, the higher elevated heat temperature resistance. Since silica fume has the highest reactive future among the other puzzoulans used in this paper, mortar sample including silica fume has the highest elevated temperature resistance compared the other samples tested. This phenomena is attributed to formation of extra tobermorite gel (CSH phase) as a result of reaction of silicafume and $Ca(OH)_2$ in cement (Saad et al., 1996).

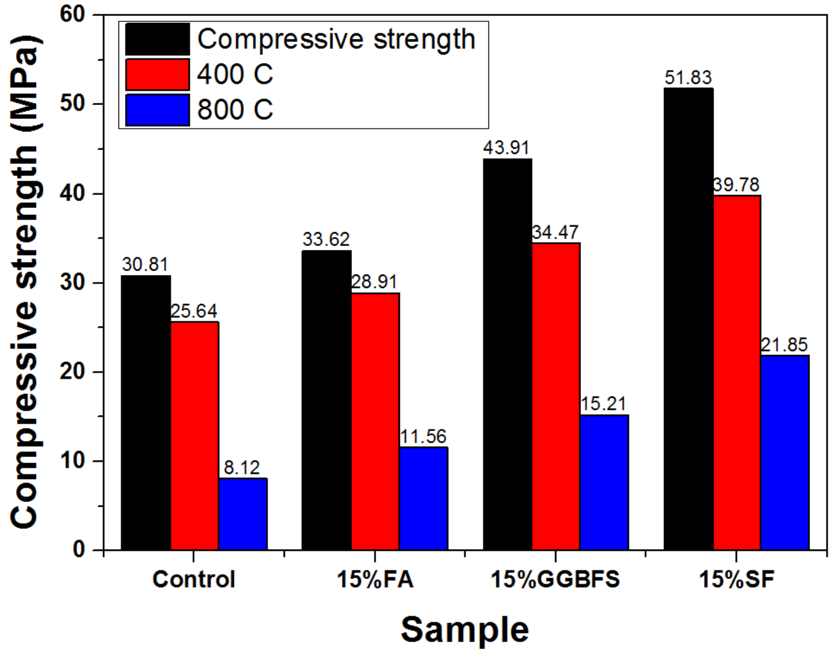

Figure 3. Compressive strength results of mortar samples with different inclusions before and after elevated heat exposure

Conclusion

In this study, elevated heat resistance of mortar samples including 15% FA, GGBFS and SF is investigated. Mortar samples with FA, GGBFS and SF are kept in a furnace for two hours at 400 $^{\circ}$C and 800 $^{\circ}$C to evaluate elevated heat resistance of the mortars. According to the findings it is revealed that replacement of 15% FA, GGBFS and SF by weight of cement in mortar specimens resulted increase in compressive strength of the mortars as expected. The highest elevated heat resistance observed in mortar samples with SF and the lowest elevated heat resistance observed in the control samples that does not include any puzzoulan. The altered heat resistance with presence of FA, GGBFS and SF is attributed to the puzzoulanic behavior of those materials. These materials react with $Ca(OH)_2$ in cement and produced extra tobermorite gel (CSH phase) that provides extra durability to the composite. This study reveals that among the studied materials SF provides the best heat resistance to the mortar.

Conflict of Interest

The author declares that there is no conflict of interest.

Author's Contribution

The contribution of the author is 100%.

References

Ahn YB., Jang JG., Lee HK. Mechanical properties of lightweight concrete made with coal ashes after exposure to elevated temperatures. Cem Concr Compos 2016; 72: 27-38.

Akbar A., Liew KM. Influence of elevated temperature on the microstructure and mechanical performance of cement composites reinforced with recycled carbon fibers. Compos Part B Eng 2020; 198.

ASTM Standard Designation C109 Standard Method for Compressive Strength of Cement Mortar, ASTM, Philadelphia, PA (2003).

ASTM C348-20. Standard test method for flexural strength of hydraulic-cement mortars. Annu B ASTM Stand 1999.

ASTM Standard. ASTM C349-18: Standard test method for compressive strength of hydraulic-cement mortars (Using Portions of Prisms Broken in Flexure). Annu B ASTM Stand 2018.

Aydin S., Baradan B. Effect of pumice and fly ash incorporation on high temperature resistance of cement based mortars. Cem Concr Res 2007; 37: 988–995.

Azari Jafari H., Taheri Amiri MJ., Ashrafian A., Rasekh H., Barforooshi MJ., Berenjian J. Ternary blended cement: An eco-friendly alternative to improve resistivity of high-performance self-consolidating concrete against elevated temperature. J Clean Prod 2019; 223: 575–586. https://doi.org/10.1016/j.jclepro.2019.03.054.

Benli A., Karatas M., Anil Toprak H. Mechanical characteristics of self-compacting mortars with raw and expanded vermiculite as partial cement replacement at elevated temperatures. Constr Build Mater 2020; 239: 117895. https://doi.org/10.1016/j.conbuildmat.2019.117895.

Biolzi L., Cattaneo S., Rosati G. Evaluating residual properties of thermally damaged concrete. Cem Concr Compos 2008; 30: 907–916. https://doi.org/10.1016/j.cemconcomp.2008.09.005.

Chan YN., Peng GF., Anson M. Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures. Cement and Concrete Composites 1999; 21(1): 23-27.

Cree D., Green M., Noumowé A. Residual strength of concrete containing recycled materials after exposure to fire: A review. Constr Build Mater 2013; 45: 208–223.

Cuesta A., Santacruz I., De la Torre AG., Dapiaggi M., Zea-Garcia JD., Aranda MAG. Local structure and Ca/Si ratio in C-S-H gels from hydration of blends of tricalcium silicate and silica fume. Cem Concr Res 2021; 143: 106405.

Çağlar H., Çağlar A., Can Ö. Graphene additives effect on mechanical and structural characterization properties of polyvinyl alcohol (PVA) and boron based cement mortar. Science of Advanced Materials, 2020; 12(2): 269-275.

Demirel B., Keleştemur O. Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume. Fire Saf J 2010; 45: 385–391.

Erşan YÇ., Van Tittelboom K., Boon N., De Belie N. Nitrite producing bacteria inhibit reinforcement bar corrosion in cementitious materials. Sci Reports 2018; 8: 1–10.

Guo Z., Jiang T., Zhang J., Kong X., Chen C., Lehman DE. Mechanical and durability properties of sustainable self-compacting concrete with recycled concrete aggregate and fly ash, slag and silica fume. Constr Build Mater 2020; 231: 117115.

Hager I. Behaviour of cement concrete at high temperature. Bull Polish Acad Sci Tech Sci 2013; 61:145–54. https://doi.org/10.2478/bpasts-2013-0013.

https://panoramakine.com.tr/default.asp?sayfa=goster&no=c3c (as viewed on October 26, 2021)

Husem M. The effects of high temperature on compressive and flexural strengths of ordinary and high-performance concrete. Fire Saf J 2006; 41: 155–163.

Jia Z., Chen C., Shi J., Zhang Y., Sun Z., Zhang P. The microstructural change of C-S-H at elevated temperature in Portland cement/GGBFS blended system. Cem Concr Res 2019; 123: 105773.

Khaliq W., Khan HA. High temperature material properties of calcium aluminate cement concrete. Constr Build Mater 2015; 94: 475–487. https://doi.org/10.1016/j.conbuildmat.2015.07.023.

Khaliq W., Kodur V. Behavior of high strength fly ash concrete columns under fire conditions. Mater Struct Constr 2013; 46: 857–867.

Khaliq W., Taimur. Mechanical and physical response of recycled aggregates high-strength concrete at elevated temperatures. Fire Saf J 2018; 96: 203–214.

Kodur VKR., Sultan MA. Effect of temperature on thermal properties of high-strength concrete. J Mater Civ Eng 2003; 15: 101–107.

Kong DLY., Sanjayan JG. Effect of elevated temperatures on geopolymer paste, mortar and concrete. Cem Concr Res 2010; 40: 334–339. https://doi.org/10.1016/j.cemconres.2009.10.017.

Liu M., Zhao Y., Xiao Y., Yu Z. Performance of cement pastes containing sewage sludge ash at elevated temperatures. Constr Build Mater 2019; 211:785–795.

Lublóy É., Kopecskó K., Balázs GL., Restás Á., Szilágyi IM. Improved fire resistance by using Portland-pozzolana or Portland-fly ash cements. J Therm Anal Calorim 2017; 129: 925–936.

Ma Q., Guo R., Zhao Z., Lin Z., He K. Mechanical properties of concrete at high temperature-A review. Constr Build Mater 2015; 93: 371–383.

Memon SA., Shah SFA., Khushnood RA., Baloch WL. Durability of sustainable concrete subjected to elevated temperature – A review. Constr Build Mater 2019; 199: 435–455. https://doi.org/10.1016/j.conbuildmat.2018.12.040.

Ming X., Cao M., Yin H. Microstructural and mechanical evolutions of sustainable cement blends containing fly ash and calcium carbonate whiskers induced by high temperature. Constr Build Mater 2020; 263: 120615. https://doi.org/10.1016/j.conbuildmat.2020.120615.

Nadeem A., Memon SA., Lo TY. Qualitative and quantitative analysis and identification of flaws in the microstructure of fly ash and metakaolin blended high performance concrete after exposure to elevated temperatures. Constr Build Mater 2013; 38: 731–741.

Nadeem A., Memon SA., Lo TY. The performance of fly ash and metakaolin concrete at elevated temperatures. Constr Build Mater 2014; 62: 67–76.

Nedunuri SSSA., Sertse SG., Muhammad S. Microstructural study of Portland cement partially replaced with fly ash, ground granulated blast furnace slag and silica fume as determined by pozzolanic activity. Constr Build Mater 2020; 238: 117561.

Poon CS., Azhar S., Anson M., Wong YL. Comparison of the strength and durability performance of normal- and high-strength pozzolanic concretes at elevated temperatures. Cem Concr Res 2001; 31: 1291–300. https://doi.org/10.1016/S0008-8846(01)00580-4.

Poon CS., Azhar S., Anson M., Wong YL. Performance of metakaolin concrete at elevated temperatures. Cem Concr Compos 2003; 25: 83–89.

Poon CS., Azhar S., Anson M., Wong YL. Strength and durability recovery of fire-damaged concrete after post-fire-curing. Cem Concr Res 2001; 31: 1307–1318.

Qu F., Li W., Tao Z., Castel A., Wang K. High temperature resistance of fly ash/GGBFS-based geopolymer mortar with load-induced damage. Mater Struct Constr 2020; 53: 1–21.

Saad M., Abo-El-Eneinf SA., Hanna GB., Kotkata MF. Effect of temperature on physical and mechanical properties of concrete containing silica fume. Cem Concr Res 1996; 26: 669–675. https://doi.org/10.1016/S0008-8846(96)85002-2.

Setayesh Gar P., Suresh N., Bindiganavile V. Sugar cane bagasse ash as a pozzolanic admixture in concrete for resistance to sustained elevated temperatures. Constr Build Mater 2017; 153: 929–936.

Wang L., Guo F., Lin Y., Yang H., Tang SW. Comparison between the effects of phosphorous slag and fly ash on the C-S-H structure, long-term hydration heat and volume deformation of cement-based materials. Constr Build Mater 2020; 250: 118807.

Zemri C., Bachir Bouiadjra M. Comparison between physical–mechanical properties of mortar made with Portland cement (CEMI) and slag cement (CEMIII) subjected to elevated temperature. Case Stud Constr Mater 2020; 12: e00339. https://doi.org/10.1016/j.cscm.2020.e00339.

Zhao Z., Qu X., Li F., Wei J. Effects of steel slag and silica fume additions on compressive strength and thermal properties of lime-fly ash pastes. Constr Build Mater 2018; 183: 439–450.

Zhou J., Lu D., Yang Y., Gong Y., Ma X., Yu B., Yan B. Physical and mechanical properties of high-strength concrete modified with supplementary cementitious materials after exposure to elevated temperature up to 1000 °C. Materials 2020; 13(3): 532.