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Residual Modulus of Elasticity of Self-Compacting Concrete Incorporated Unprocessed Waste Fly Ash after Expose to the Elevated Temperature

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Abstract—The present study experimentally investigated the impact of incorporating unprocessed waste fly ash (UWFA) on the residual mechanical properties of self-compacting concrete (SCC) after exposure to elevated temperature. Three mixtures of SCC have been produced by replacing the cement mass by 0%, 15% and 30% of UWFA. Generally, the fire resistance of SCC has been enhanced by replacing the cement up to 15% of UWFA, especially in case of residual modulus of elasticity which considers more sensitive than other mechanical properties at elevated temperature. However, a strong linear relationship has been observed between the residual flexural strength and modulus of elasticity, where both of them affected significantly by the cracks appearance and propagation as a result of elevated temperature. Sustainable products could be produced by incorporating unprocessed waste powder materials in the production of concrete, where the waste materials, CO_2 emissions, and the energy needed for processing are reduced.

Keywords—Self-compacting high-performance concrete, unprocessed waste fly ash, fire resistance, residual modulus of elasticity.

I. Introduction

THE binder in concrete could be cement alone or incorporation of cement with other cement replacing materials (CRMs) like pulverized fly ash, silica fume, slag, limestone, etc., which generally affects the properties of concrete at both ambient and elevated temperatures either positively or negatively. CRMs are important ingredients for producing concrete with high-performance abilities. Poon et al. and Tang and Lo [1], [2] agreed with the positive effect of pulverized fly ash on the residual mechanical properties of concrete after exposure to the elevated temperatures as well as decreasing the possibility of spalling and the appearance of surface cracks. Hanaa et al. [3] investigated the effect the elevated temperature on the modulus of elasticity for the vibrated concrete and SCC and found that the SCC performed slightly better than the vibrated concrete. Where that the elevated temperature decreases the strength and increases the cracks, as well as certain condition spalling can occur. Bui et al. and Li et al. [4], [5] found that modulus of elasticity is more sensitive to the elevated temperature than other mechanical properties and the mineral admixtures enhance the modulus of elasticity performance after elevated temperature. Hamood et al. [6] investigated the utilization of UWFA in place of cement and found that increasing the replacement amount of cement by UWFA reduced the flowability and mechanical properties at an early stage but improved the long-term properties. They recommended the use of UWFA for producing SCC. Poon et al. [7] investigated the pozzolanic properties of UWFA-blended cement pastes. They observed that a high but not excessive water-to-binder (w/b) ratio could improve the reactivity of UWFA owing to the high water absorption of WFA. Snelson and Kinuthia (a and b) [8], [9] investigated the physical, mechanical and durability characteristics of concrete and cement paste using WFA, and their results confirmed the possibility of utilizing UWFA in various concrete works, although caution should be taken to avoid excessive cement replacement. Meanwhile, the incorporation of UWFA in concrete from all aspects, especially the activation behavior of the binder itself with time, has not been discussed.

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II. Materials

A. Cement and UWFA

The cement used to conduct the present study was a Portland cement (CEM I 42.5N) in accordance with EN 197-1:2000 [10] to eliminate the effect of mineral admixtures of manufactured cement on the test and to investigate the impact of the used UWFA which partially replaced the cement. It is non-polarized fly ash collected from a coal power station in Hungary and delivered to the laboratory without any kind processing; Visonta coal-fired thermal power station is the coal power station from where the UWFA has been imported.

The oxidizing composition of the cement and UWFA has been determined by chemical analytical methods, where the x-ray diffraction profiles for them are shown in Fig. 1, and the chemical compositions and physical properties of the cement and UWFA are shown in Table I, which were tested in accordance with the EN 196-2:2013 and EN 525-12:2014 [11], [12].

Fig. 2 shows the sieve curves for both cement and UWFA. However, the crystalline phases could be identified as:

1. Cement (CEM I): Ca_3SiO_5 (C3S, alite, hatrurite) as main crystalline component; Ca_2SiO_4 (C3S, belite, larnite) presence cannot be excluded; $CaSO_4.2H_2O$ (CSH_2, gypsum); $Ca_4Al_2Fe_2O_{10}$ (C4AF, brownmillerite),
2. UWFA: α-SiO_2 (S, α-quartz) as main crystalline

component; - Fe_2O_3 (F, hematite) also dominating crystalline component; - $CaSO_4$ (CS, anhydrite); - plagioclase (feldspar, most probable heat-treated albite).

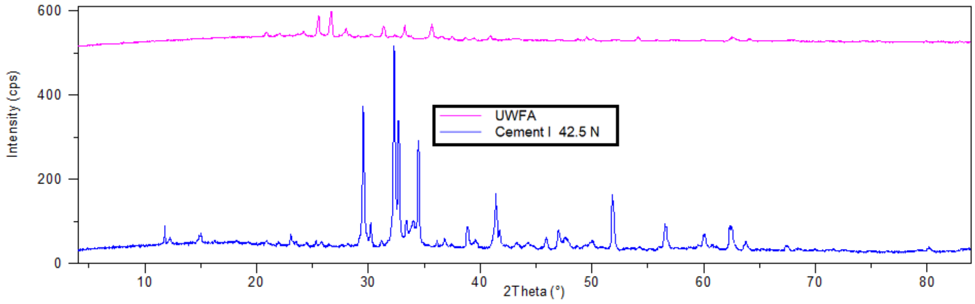

Fig. 1 X-ray diffraction profile for cement and UWFA

TABLE I
CHEMICAL COMPOSITIONS AND PHYSICAL PROPERTIES OF CEMENT AND UWFA

Measured Property	CEM I	UWFA
Density (g/cm^3)	3.02	2.15
Specific surface area (cm^2/g)	3326	4323
Loss on ignition	3.0	1.95
SiO_2	19.33	43.02
CaO	63.43	15.07
MgO	1.45	3.14
Fe_2O_3	3.42	14.17
Al_2O_3	4.67	15.6
SO_3	2.6	3.56
Chloride content	0.04	0.02
Free CaO	0.71	0.37
Insoluble part in dilute hydrochloric acid and sodium carbonate	0.26	49.72

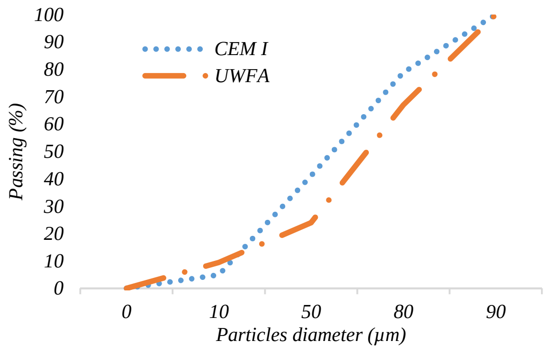

Fig. 2 Grading curves of cement and UWFA

B. Aggregates

Quartz sand and gravel (0/16 mm size), which have been imported with two nominal grading fractions; sand (0/4 mm) and gravel (4/16 mm), and divided in accordance with the fractions to 45% and 55%, respectively, based on authors optimization mix proportion. It has been tested to meet the requirements of EN 12620:2002+A1:2008 [13]. The grading curves of sand and gravel are presented in Fig. 3.

III. Concrete Mixtures

UWFA was tested for the activation index of the compressive strength test of cement paste samples (with w/b ratio = 0.35), with 10% to 60% incorporated amounts of the UWFA as a CRM. Activity index is expressed by the ratio of the strength of the cement paste mixture containing CRMs replacement and strength of the reference mixture (only cement), which expresses the hydration rate of the CRMs [14]. The specimens were tested at three curing ages (7 days, 28 days, and 90 days).

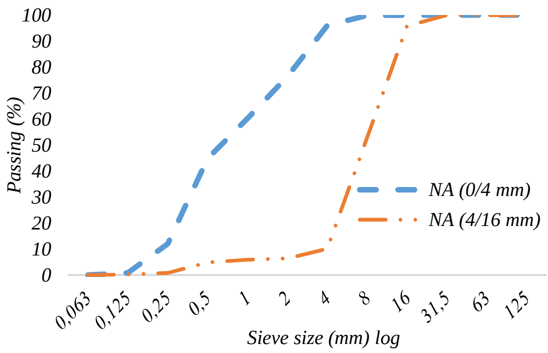

Fig. 3 Grading curves Grading curves of NA and RCA

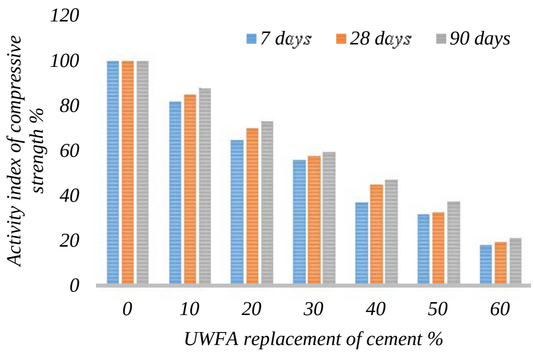

Fig. 4 Impact of UWFA amount on the activity index

As shown in Fig. 4, significant reduction in the compressive strength has occurred by replacing the cement with more than 30% of UWFA. However, the activation index value increases by time in the case of all replacing amounts of cement by

UWFA (up to 60%); thus, and based on the cement paste study, which is conducted to investigate the activation index of the UWFA, cement was replaced by 15% and 30% by UWFA. The results of the UWFA's activation index have been published by the authors [15], [16], and the study concluded that UWFA needs a long time for observing its hydration activity. Three SCC mixtures have been produced, where the UWFA mass individually replaced the cement mass partially by 0%, 15% and 30%, respectively. The w/b ratio was 0.35 for all mixtures with constant binder amount of 500 kg/m^3. The relatively low w/b ratio content was selected to achieve high performance of the produced concrete; meanwhile, a considerable amount of the superplasticizer has been used to achieve the self compactivity. The used mixing water was tap water that complies with the requirements of EN 1008:2002 [17]. The mixing proportions for all mixtures are shown in Table II.

TABLE II
CONCRETE MIXING PROPORTIONING

Name of mixture	Proportions in kg/m^3					
	CEM I 42.5 N	UWFA	Fine aggregate 0/4	Coarse aggregate 4/16	Superplasticizer	Water
Reference	500	0	783	939	1.5	175
15UWFA	425	75	767	920	2	175
30UWFA	350	150	751	901	3	175

The specimens have been tested at age of 95 ± 5 days (three months) as recommended by RILEM, and starts by heating up the specimens to the maximum temperature for two hours, then cooling them down at laboratory conditions until the testing time around 24 hours later. The maximum temperatures were up to 800°C, which is the equivalent of the temperature that can be reached in one hour in a real fire situation [18]. The heating curve was just the same as the standard fire ISO 834 heating curve EN 1991-1-2:2002 [19], which is shown in Fig. 5. Compressive strength, three points flexural strength and modulus of elasticity tests were carried out for investigating the residual mechanical properties of SCC specimens after exposure to the elevated temperatures, which were tested in accordance with the EN 12390-3:2009, EN 14146:2004 and EN 14146:2004 [20]–[22], respectively. For each mixture and at each temperature degree, three 150x150x150 mm cubes have been tested for compressive strength and six 70x70x250 mm prisms have been tested for modulus of elasticity and then tested for flexural strength where the modulus of elasticity test is a non-destructive test, thus 54 cubes and 108 prisms have been tested through the present study.

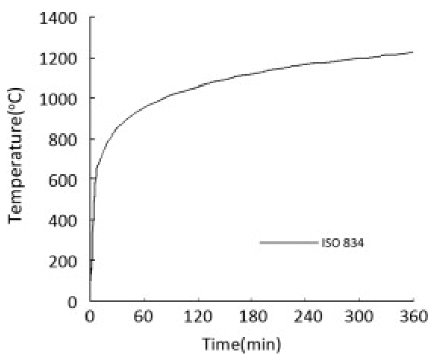

Fig. 5 ISO-834 fire curve

IV. Results and Discussion

A. Results at Laboratory Temperature

All mixtures have satisfied the European guideline for SCC [23] based on the consistency tests of SCC (slump flow and V-Funnel tests). The compressive strength, flexural strength and modulus of elasticity have been tested at ambient temperature at age of 90 days, where in case of incorporating UWFA, the rate of gaining strength was higher after 28 days because of the hydration process of UWFA which is slower than the cement. However, the mechanical properties are not significantly affected. Fig. 6 shows the compressive strength, flexural strength and modulus of elasticity results after 90 days for all the three SCC mixtures. The results in Fig. 6 have been published for the authors [24].

B. Results at Elevated Temperatures

Using unprocessed waste powder materials as CRMs like UWFA gives a sustainable value to the SCC. Figs. 7 and 8 show the development of relative residual compressive and flexural strengths as a function of temperature in the case of three replacement amounts of cement by UWFA. UWFA composition was close to the cement composition thus it did not remarkably affect the fire resistance compared to the reference when it behaved similarly as did the cement binder in the reference mixture. Nevertheless, it enhanced the residual compressive strength after considerable temperature elevation due to the excessive hydration of UWFA with age. This condition could be also related to its composition, which featured a small amount of CaO. The low CaO/SiO_2 ratio of the binder means higher relative residual compressive strength [25], as shown in Table III that CaO in the UWFA is relatively low compared to the amount of SiO_2.

The optimal replacement amount of cement by UWFA as a function of the elevated temperature was 15%. Modulus of elasticity is more sensitive to high temperatures than other mechanical properties and shows precisely the effect of incorporating CRMs with concrete. Fig. 9 shows the development of relative residual modulus of elasticity as a

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function of temperature in the case of three replacement amounts of cement by UWFA.

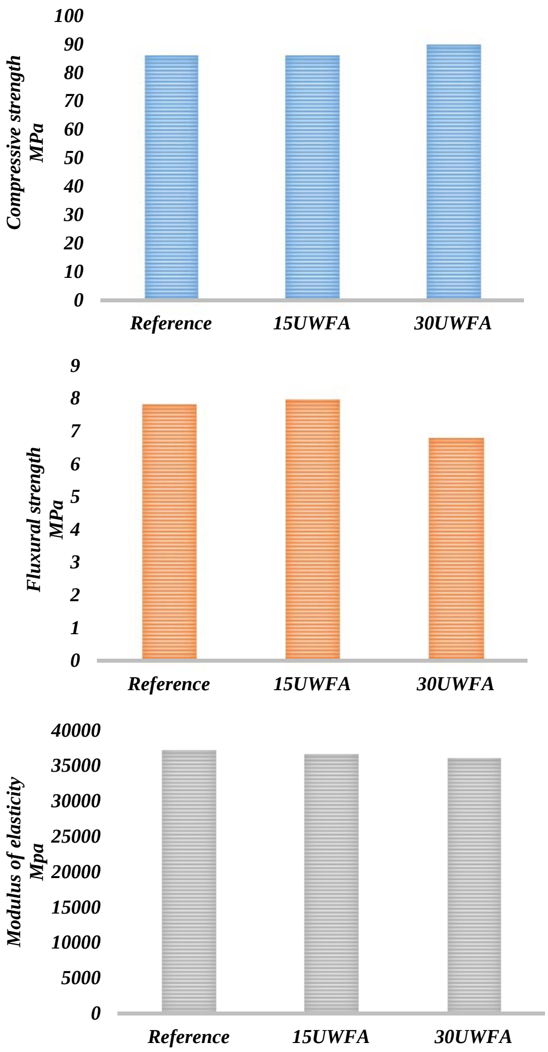

Fig. 6 Compressive strength, flexural strength and modulus of elasticity at laboratory temperature (90 days)

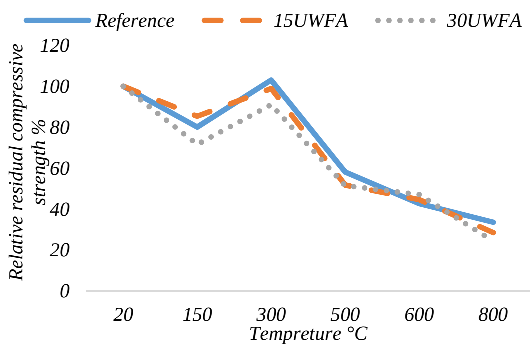

Fig. 7 Relative residual compressive strengths as a function of temperature of SCC incorporated UWFA up to 30% as a replacement of cement

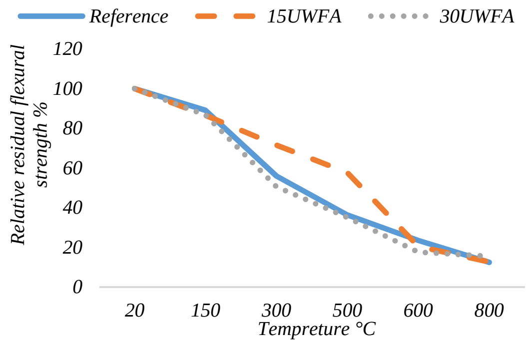

Fig. 8 Relative residual flexural strengths as a function of temperature of SCC incorporated UWFA up to 30% as a replacement of cement

TABLE III
RATIOS OF THE THREE MAIN OXIDES IN CEMENT COMPOSITIONS

Powder material	SiO_2	CaO	CaO/SiO_2
CEM I	20.21	66.31	328.14
UWFA	45.31	15.87	35.03

It is clear that using 30% of UWFA caused significant deterioration on the residual modulus of elasticity due to the appearance and propagation of significant amount of cracks. As well, after exposing the concrete to 800°C it was difficult to conduct the modulus of elasticity test due to the high fragility of the specimens.

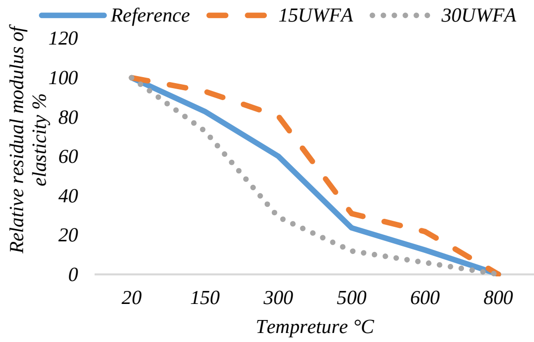

Fig. 9 Relative residual modulus of elasticity as a function of temperature of SCC incorporated UWFA up to 30% as a replacement of cement

It was found that there is a strong linear relationship between the residual modulus of elasticity and flexural strength, where both of them are affected by the appearance of cracks and the volume of binder; as well, they are less affected by the discharging of water like in the case of compressive strength. Thus, the residual modulus of elasticity and flexural strength of SCC behaves almost in the same tendency after exposure to the elevated temperature.

Fig. 10 shows the linear relationship between the residual modulus of elasticity and residual flexural strength as a function of temperature in the case of three replacement amounts of cement by UWFA.

Fig. 11 shows that the crack appearance has been decreased in case of using UWFA comparing with reference mixture and that agreed with Poon et al. and Tang and Lo [1], [2] who tested the effect of pulverized fly ash on the residual mechanical properties of concrete after exposure to the elevated temperatures. They observed decreasing the possibility of spalling and the appearance of surface cracks. That is because of the ability of UWFA to refill the network of fine cracks by postfire curing [26]. However, the cracks were clear at the higher temperature because the is concrete considered to be high strength concrete, and usually the surface cracking is more clear in the case of high strength concrete than normal strength concrete.

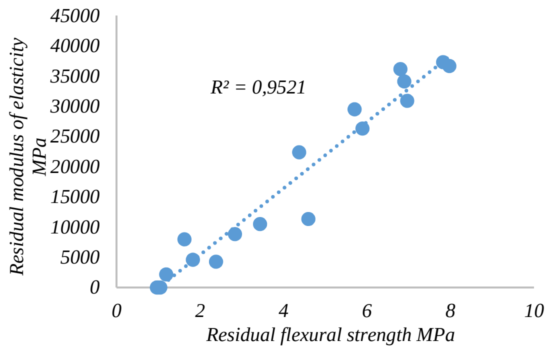

Fig. 10 Relationship between the residual flexural strengths and residual modulus of elasticity as a function of temperature of SCC incorporated UWFA up to 30% as a replacement of cement

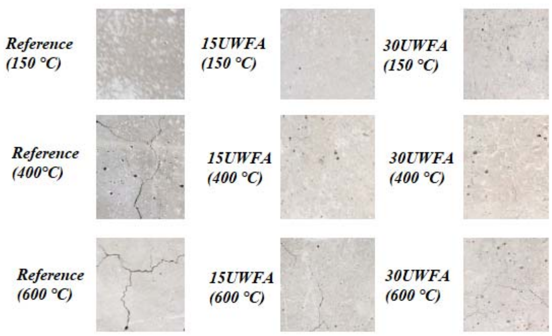

Fig. 11 Typical crack patterns

V. Conclusion

The incorporation of UWFA in SCC offer not only sustainability, but also increased the resistance of concrete structures against special circumstances. However, the following conclusions could be drawn:

1. The optimal replacement amount of cement by UWFA as a function of the elevated temperature was 15%. However, using high dosage UWFA is not recommended, where the mechanical properties have been deteriorated after elevated temperatures.
2. UWFA had no remarkable effect on resistance against high temperatures, nevertheless decreasing the surface cracks up to 600°C. Meanwhile, it had a considerably positive effect on resistance against high temperatures due to its low CaO content, which enhanced the fire resistance at high temperatures, as well as its grading.
3. Modulus of elasticity is more sensitive to the elevated temperate than the other mechanical properties due to its sensitivity to the cracks' appearance and propagation.
4. There is a strong linear relationship between the flexural strength and modulus of elasticity after exposure to the elevated temperature.

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