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Influence of elevated temperatures on the mechanical properties and microstructure of self consolidating lightweight aggregate concrete

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ABSTRACT

Self consolidating lightweight concrete (SCLWC) mixtures were prepared by using two different lightweight coarse aggregates and by replacing normal weight crushed coarse limestone aggregate at a constant water/powder ratio. One of the SCLWC mixtures was also prepared at different water/powder ratios. All the mixtures were exposed to 300, 600 and 900 °C, respectively. Lightweight aggregate type and water/powder ratio affect water transport characteristics and resistance of the mixtures to elevated temperatures. The microstructural investigation findings are consistent with thermal strain and residual mechanical properties of the mixtures after exposure to high temperatures.

1. Introduction

Structural lightweight concrete is advantageous in terms of reducing the dead load of the structures and the lateral earthquake loads. In addition to lower density, lightweight concrete (LWC) has a better thermal insulation than conventional concrete. The interfacial transition zone (ITZ) characteristics of lightweight aggregate concretes are different from that of conventional concretes. The improvement of paste–aggregate bonding by penetration of cement paste into surface pores of aggregates and decreasing the amount of internal bleed water are important characteristics [1–3]. This also explains why lightweight concretes have equal or lower permeability when compared to its normal weight counterpart [4]. Furthermore, as distinct from conventional concrete, the weakest link seems to be the aggregate itself, not the ITZ. Thus, the strength levels of lightweight concrete mixtures are quite dependent on the specific gravity of the aggregates used [5]. Density of lightweight aggregates and w/c ratio are the two main determining factors of LWC mechanical properties. Therefore, for a constant w/c ratio, higher strength levels may be achieved by using lightweight aggregates having higher specific gravity values. The elastic modulus of lightweight aggregates is compatible with that of cement paste, which reduces the tendency for ITZ microcracking [1]. Structural LWC is mixed, produced, transported and placed in a similar manner as conventional concrete. However, due to the low density of aggregates used in the production of structural LWC, segregation problems may arise. Precast concrete production methods necessitating the utilisation of external vibrators may decrease the resistance to segregation. Lightweight aggregates need more paste to achieve the same workability and designed compressive strength when compared to normal weight aggregates. This is also a challenge for producing durable LWC mixtures for structural applications [5].

Self-consolidating concrete (SCC), one of the latest achievements of concrete technology, has been first developed by Japanese researchers with an intent to increase the durability of reinforced concrete structures by increasing the workability of concrete and thus by increasing the construction quality. It can flow easily filling the gaps between reinforcement and corners of the moulds without vibration. SCC can be placed on site or produced for precast applications. SCC is a dense and resultantly durable concrete with well-known design techniques. Two important design methods are as follows. Japanese method was suggested by Okamura [6], Okamura and Ouchi [7] and the Chinese method was suggested by Su et al. [8] and Su and Miao [9]. Still being a special concrete mixture, the share of SCC production among total concrete produced has an increasing trend in Asia (predominantly Japan), Europe, North and South America [10–12]. Although many studies are available in the literature about the durability of SCC [13–20], due to its relatively short history in practical applications, field performance records of SCC structures date back to only a few decades.

Using a proper method based on SCC mix design methodology, it is possible to design self consolidating lightweight concrete (SCLWC) mixture having superior fresh and hardened concrete properties [5,21–26]. Self-consolidating lightweight concrete also

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provide an alternative way of producing LWC mixtures for structural applications with proper strength and durability without segregation.

Andiç-Çakır et al. [22] studied the mechanical properties of structural SCLWC mixtures. The results indicate that there is a good positive correlation between 28-day compressive strength and unit weight of SCLWC mixtures. Additionally, the decrease in flexural strength owing to the addition of lightweight aggregate is relatively less than the reduction in compressive and splitting tensile strength. This behaviour may be attributed to the improvement in the ITZ of SCLWC mixtures compared to SCC mixtures. Similarly, Kim et al. [25] observed a greater reduction rate in compressive strength compared to that of concrete density.

Transport properties of SCC are related to water/binder (w/b) or water/powder (w/p) ratio. Moreover, SCLWC has a higher porosity due to incorporation of porous lightweight aggregates. Gönen [26] reported that the typical porosity values for SCLWC containing pumice is 22–29%, while these values range between 13% and 19% for SCC produced with crushed limestone. Additionally, water penetration under pressure and resistance to elevated temperatures were higher for SCLWC compared to SCC. The enhanced resistance to fluid transport of SCC mixtures which is more significant at high w/b ratios is attributed to its refined pore structure and more uniform ITZ characteristics. Moreover, more or less related to its fluid transport mechanisms, SCC has a tendency to spalling upon exposure to elevated temperatures if its moisture content is high [15,19]. Bakhtiyari et al. [27] tested the fire resistance of unloaded SCC specimens at temperatures of 150, 500, 750 and 1000 °C and compared the results with those of conventional concretes. The strength loss of conventional concretes after elevated temperatures were more than that of SCCs, however, SCCs were more susceptible to spalling. The spalling behaviour of high performance concretes may be controlled by the incorporation of synthetic fibres. Melting of fibres at 900° c leads to an increase of porosity of such systems reducing the spalling behaviour, however, their effect on residual strength is still under discussion [28–31]. Analogously, lightweight aggregate replacement in SCC mixtures may serve for the same purpose due to its porous characteristics. However, contradictory results in the literature shows that lightweight concrete may also show high degree of spalling during fire tests depending on various factors, e.g., critical moisture content, permeability of concrete, mechanical loading during fire and type of the test [32,33]. The possible reasons for a tendency of spalling are increased amount of evaporable water due to higher moisture content of lightweight aggregates acting like water reservoirs, lower permeability of the mixtures leading to higher vapour pressures and lower heat conductivity leading to higher temperature gradients [34].

Fares et al. [35] investigated the effect of high temperatures on some physical and mechanical properties of SCC. Their experimental findings confirm that the change in the intrinsic permeability of the specimens shows a good correlation with their residual compressive strength and concrete damage, respectively. Kodur and Khaliq [36] studied the effect of high temperatures on the thermal properties of special types of high strength concretes. The authors indicate that thermal expansion increases with temperature up to 800 °C and SCC shows higher thermal expansion values compared to high strength concrete and fly ash incorporating concrete. Fibre addition also changes the thermal expansion trends of the mixtures. Uygunoğlu and Topçu [37] determined the thermal strain and coefficient of thermal expansion (CTE) of limestone and lightweight aggregate containing SCCs by using dilatometer method. The authors stated that the CTE values were considerably lower for the self consolidating concrete series produced with lightweight pumice aggregate when compared to that of self consolidating concretes produced with limestone aggregate. Besides, the thermal strain of SCLWC mixtures may show negative values upon exposure to high temperatures while the SCC mixtures revealed positive thermal strain values. This behaviour was attributed to the shrinking of pumice aggregate under elevated temperatures. Additionally, thermal strain was also related to w/p ratio of the mixtures, decreasing by increasing w/p ratio.

Due to its various advantages, mainly high strength/weight ratio and ease of production, SCLWC is recognised as a special type of concrete for construction industry. Ready-mixed SCLWC can be an alternative for conventional concrete especially in the case of narrow reinforcement gaps, and in the case where vibration is avoided, e.g., production of precast and prefabricated concrete elements, high rise buildings, tunnels and other forms of infrastructures. As a novel concrete type, the fire resistance of SCLWC has not yet been studied thoroughly; moreover, the experimental accumulation of knowledge on the fire resistance of structural LWC and SCC is insufficient to explain the mechanism of deterioration of SCLWC when exposed to elevated temperatures. In this study, it is aimed to investigate the high temperature resistance of lightweight aggregate concrete mixtures regarding to their porosity and water transport characteristics. The mixtures were designed for precast concrete production. Self consolidating mixtures having constant water/powder ratios were designed by using two different lightweight aggregates and a normal weight crushed limestone as coarse aggregate. One of the SCLWC mixtures was also prepared by using different water/powder ratios. The findings of this study were evaluated by investigating the residual mechanical and microstructural properties and thermal strain values of the samples exposed to elevated temperatures.

2. Materials and methods

2.1. Materials

2.1.1. Cement and filler

CEM I 42.5 R type Portland cement (similar to ASTM Type-I) confirming the requirements of EN 197-1 [38] was used in this study. An industrial waste of olivine powder with maximum particle size of 75 μm was used to increase the powder content of SCLWC mixture. Chemical composition and physical properties of Portland cement and olivine powder are presented in Table 1.

In order to investigate the effect of olivine powder on compressive strength properties, mortar mixtures were prepared in accordance with EN 196-1 [39] where CEN standard sand was used. Compressive strength of neat cement mortar is 49.9 MPa and 51.4 MPa at 7 and 28-days, respectively. Additional mortars were prepared with 10%, 20% and 30% olivine powder replaced with cement and tested at 28-days. Strength activity indices of these mixtures were obtained as 74%, 73% and 49%, respectively. Another test series were cast by replacing the olivine powder by filler portion (<75 μm) of standard sand. Compressive strength test results of these series revealed a 15% increase at 7-days and 4% decrease at 28-days compared to that of control mixture. The results reveal that olivine powder may be used as a fine material to improve the self consolidating characteristics of concrete mixtures.

2.1.2. Aggregates

Three types of aggregates, a crushed limestone aggregate and two pumice aggregates obtained from different sources were used in this study. Normal weight limestone aggregate (LS) was used as fine aggregate in all series. Lightweight

Table 1
Chemical composition of powders.

Chemical composition (%)	Cement	Olivine powder
SiO_2	18.59	45.80
Al_2O_3	4.75	1.59
Fe_2O_3	3.41	5.32
CaO	63.59	1.42
MgO	1.11	44.53
Na_2O	0.49	0.51
K_2O	0.77	0.10
SO_3	3.39	–
Cr_2O_3	–	0.72
Cl	0.016	–
Loss on ignition	3.03	1.10
Free CaO	1.56	–
Specific gravity	3.11	3.10