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The High Temperature Effect on Fibre Reinforced Self Compacting Lightweight Concrete Designed with Single and Hybrid Fibres

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The purpose of this paper is to declare the results of investigation conducted on design of fibre reinforced self compacting lightweight concrete which has three different concrete technologies, and high temperature effect on it. For this aim, it is desired that production of new kind concrete material composed of fibre reinforced concrete, self compacting concrete and structural lightweight concrete technologies using all their better benefits. In this study, fly ash was used as a powder to reduce Portland cement consumption as well as CO_2 emission through the use of that waste material. A control self compacting concrete and 7 fibre reinforced self compacting lightweight concretes were designed applying slump flow (T50-flowing time and flowing diameter) and V-funnel tests to determine fresh concrete properties. In the design of fibre reinforced self compacting lightweight concrete, both single and hybrid fibre reinforced self compacting lightweight concrete mixes were produced using 1 macro and 1 micro steel fibres in different lengths and aspect ratios. Hybrid fibre reinforced self compacting lightweight concrete mixes were prepared using macro fibres together with micro fibre at three different percentages (50%–50%, 25%–75%, 75%–25%) by weight. After design process, cubic and prismatic concrete specimens were produced to determine hardened properties at standard concrete age. Firstly, flexural tensile and compressive strength tests were performed on the concrete specimens on 28 day. Lastly, the concrete specimens were heated up to temperatures of 200, 400, 600 and 800 °C then compressive strength and flexural tensile tests were performed to identify high temperature effect comparing to strength test results obtained from standard laboratory conditions. The test results showed that concrete mixes including macro fibres gave the best tensile strength properties, although they gave the worst fresh concrete properties.

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1. Introduction

Recent concrete addition materials have enabled to produce concrete types having different properties for different usage aims. Fibre reinforced concrete (FRC) is an example for that kind of concretes which are including fibres spreading coincidentally at three dimensions in the matrix [1, 2]. Hybrid FRC is also a new kind of composite material produced adding different type, shape and dimensions of fibres in a concrete mix [3]. FRC produced using fibre types including different shape and dimensional properties instead of single fibre will give higher engineering advantages and more serviceable abilities [4]. In the last three decades, usage of FRC has continuously increased and remarkable improvements have been observed [1, 5]. During the development of the concrete technology, another one of the most important improvements has been the self compacting concrete (SCC) developed firstly in Japan at the end of the 1980's which can be described as a concrete type which fills the forms and consolidates with its self weight [6, 7]. There are so many existing SCC studies in the literature and they are generally on new concrete design.

As for the structural lightweight concrete (SLWC), another special concrete, has advantages because of reducing the dead load of the structures and the lateral earthquake loads. It has both lower density and better thermal insulation properties than conventional concrete as well [8]. Özkul et al. [9], after explaining basic principle and properties of SCC, they investigated some durability properties of SCC such as water absorption and permeability, carbonation resistance and chloride penetration. Arisoy and Wu [10] researched material characteristics of high performance lightweight concrete reinforced with polyvinyl alcohol fibre. Topçu and Uygunoğlu [11] made a study on effect of aggregate type on properties of hardened self-consolidating lightweight concrete. Their experimental study results emphasised that self-consolidating lightweight concrete with lightweight aggregate in lower unit weight has lower mechanical and physical properties except for thermal properties when compared to properties of SCC. Sahmaran et al. [12] investigated the workability properties of hybrid FRSCC and declared that SCC in comparison with FRC was a relatively new kind of concrete technology due to its advantages as flowability. Moreover, they reported that fibre volume, length and aspect ratios had a quantifiable effect on workability properties of hybrid FRSCC while shape and surface roughness of fibres had importance but their effect could not be clarified based on their research parameters. Corinaldesi and Moriconi [13] worked on durable FRSCC to produce thin precast elements. In the manufacturing process, they used steel fibre instead of ordinary steel-reinforcement mesh. They conducted out compressive and flexural strength tests besides durability tests such as freezing-thawing, carbonation etc. Barros et al. [14] made a study on lightweight panels of steel fibre reinforced self compacting concrete. They analysed the influence of the age on the steel fibre reinforced self compacting concrete fracture parameters. Mazaheripour et al. [15] implemented an experimental study about the effect of polypropylene fibres on the properties of fresh and hardened lightweight self-compacting concrete. They declared that fresh properties of designed concrete were badly affected by adding fibres while hardened properties were improved except compressive strength and elastic modulus.

Construction systems in Turkey are produced with concrete material and they have generally big capacity and complexity. Such construction design is a disadvantage for countries like Turkey in the aspect of earthquake and similar disaster menace [1]. Under the constraints such as market demand, earthquake and resembling disasters, combination of those three different special concretes, FRC, SCC and SLWC, will constitute FRSCLWC giving wider engineering and technical advantages. In this way, a new special concrete type eliminating each other's negative features in both fresh and hardened situations, and having better engineering properties will be designed. In addition, fly ash usage will provide an advantage in terms of sustainability.

2. Materials, methods and testing

Cement used in the study was CEM I 42.5 Class N and provided from Elazığ in Turkey. Fly ash was obtained from Kangal Power Plant in Sivas in Turkey. The specific chemical composition and some physical properties of Portland cement and fly ash are given in Table I. Total powder ratio of all designed mixtures was 28.9% in the mix proportion (see Table II). Fly ash constituted 20% of total powder by volume. The fine and coarse aggregates which are used were volcanic pumice from Elazığ in Turkey and nominal maximum size of volcanic pumice was 16 mm. Specific gravity and water absorption percentages of fine and coarse volcanic pumice aggregates are 2.05 kg/dm^3, 1.90 kg/dm^3, 18%, and 8.50%, respectively. Los Angeles abrasion test result of coarse volcanic pumice aggregate was 42%.

TABLE I

Specific chemical and some physical properties of cement and fly ash.

Chemical properties [%]							Physical properties			
Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI	Blaine	Spec. gr.	f_{ce}
CEM I 42.5 N	21.10	5.60	3.20	62.90	2.70	2.30	1.80	3370	3.10	51.70
fly ash	38.30	16.70	5.10	27.60	1.60	4.40	0.80	2345	2.50	18.10*

* Together with Portland cement.

TABLE II

Mix proportions obtained from design process (percentages of total material weight).

Series	Cement	Fly ash	Water	Fine aggr.	Coarse aggr.	Fibre	HP*
L1 (100%L)	23.2	5.7	9.5	29.5	29.5	2.6	1.4
L2 (50%L)	23.4	5.9	9.6	29.9	29.9	1.3	1.4
S1 (100%S)	23.2	5.7	9.5	29.5	29.5	2.6	1.4
S2 (50%S)	23.4	5.9	9.6	29.9	29.9	1.3	1.4
H1 (50%L+50%S)	23.2	5.7	9.5	29.5	29.5	2.6	1.4
H2 (25%L+75%S)	23.2	5.7	9.5	29.5	29.5	2.6	1.4
H3 (75%L+25%S)	23.2	5.7	9.5	29.5	29.5	2.6	1.4
C	23.7	6	9.7	30.3	30.3	–	1.1

In the study, high performance third generation hyper-plasticiser was used as a chemical addition. Hyper-plasticiser was added to mixes based on cement percentage. That chemical product has provided both high level of water decrease and long time of workability. Some technical details about hyper-plasticiser are that density at 20 °C was 1.07–1.11 kg/l, ph was 3–7 and freezing point was −9 °C. Two different type steel fibres were used in the study.

Differences between those fibres (L1 and S1) are shown in Table III. In the mix design, those fibres were used firstly as single and secondly as hybrid in two different percentages combination of macro and micro fibres. In the single design, fibres were used in two different volume proportions (50 kg/m^3 and 25 kg/m^3) to observe the effect of fibre quantity. As for the hybrid design, firstly macro fibre was used together with micro fibre at the percentage of 50%–50% by weight. Through this way, first group of hybrid fibre mixes was obtained. In the second group of hybrid combinations, 75% of micro fibre was used together with 25% of macro fibres. Lastly, 75% of macro fibre was used together with 25% of micro fibres.

Of course, a control SCC (C) with lightweight aggregates was also designed to compare with FRSCLWCs results.

TABLE III

Fibres specifications.

Fibre codes	Length, asp. ratio	Spec. gr. [kg/dm^3]	Strength [MPa]	Geometry
L (macro fibre)	30 mm, 55	7.85	Min 1100	hooked end
S (micro fibre)	6 mm, 40	7.17	2000	straight

The details related to mix designs are given in Table II. In this study, slump-flow (T_{500} and flowing diameter) and V-funnel tests were applied to be able to design FRSCLWC and control C mixes [16]. Compressive strength test was performed after 28-days water curing to identify standard strength property based on Turkish Standard [17]. Each FRSCLWC and control SCSLWC series were prepared number of three samples for compressive strength test in the dimensions of 100 mm × 100 mm × 100 mm ($L \times W \times H$). Three point flexural tensile strength tests were applied like compressive strength test. In the flexural tensile strength test, concrete samples had the dimensions of 75 mm × 75 mm × 300 mm. Then, heating test was conducted out on the concrete specimens up to temperatures of 200, 400, 600 and 800 °C. After heating test, compressive strength and flexural tensile tests were performed to identify high temperature effect comparing to strength test results obtaining from standard laboratory conditions.

3. Results and discussion

Fresh concrete properties of 10 FRSCLWC mixes and control mix C were given in Table IV and Fig. 1. As a general result, usage of small fibre in the single FRSCLWC mix design and decrease of the long fibres density in the both single and hybrid FRSCLWC mix design caused an improvement on fresh properties of FRSCLWC. As can be seen from Table IV, slump-flow diameters of all concrete series changed between 610 and 700 mm. Control concrete series (C) gave the best flowing diameter. Slump flow time and V-funnel time results also confirmed the general result mentioned above. Namely, the longest flow time through the V-funnel were obtained from the series L1 which had longest single fibre and secondly followed by coded H3 which had high density of long fibre in the hybrid mix.

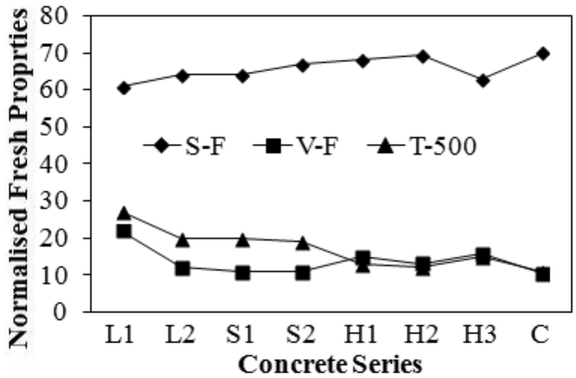

Fig. 1. Normalised fresh concrete properties test results of designed concrete series.

TABLE IV

Fresh concrete properties of designed series.

Mix type	Slump-flow diameter [mm]	Slump-flow time/T_{500} [ns]	V-Funnel [ns]	Mix type	Slump-flow diameter [mm]	Slump-flow time/T_{500} [ns]	V-funnel [ns]
L1	610	2.7	22	H1	680	1.3	14.9
L2	640	2.0	12	H2	695	1.2	13.1
S1	640	2.0	11	H3	630	1.5	15.7
S2	670	1.9	11	C	700	1.1	10.3

It is clearly seen from Fig. 1 that 50% and 75% decrease of the long fibres density in the total volume of the hybrid fibre mix caused big development on the fresh properties tests. As a conclusion, based on Fig. 1 including normalised fresh properties results, the higher volume of the fibres in the mix design has caused the lower fresh properties and in the hybrid mix design, usage of high volume micro fibre led to improvement of fresh properties.

Figure 2a and b presents real compressive strength (MPa) and residual percentage of compressive strength results of the all concrete series before and after heating test. It can be seen that all concrete series gave similar compressive strength performances in the same condition. These results are quite normal because all experimental parameters are the same except fibre inclusion and properties, its aspect ratio and different fibre mix in the design (see Tables II, III). Nonetheless, the lowest compressive strength results were obtained from the series L1 including coded L fibre while series H2 was giving the best results containing %25L+%75S hybrid fibres in all temperature conditions. In general, FRSCLWCs including macro fibres gave lower compressive strengths than series C, although FRSCLWCs including micro fibres gave higher compressive strengths, relatively similar with series C (see Fig. 2a). Sahmaran and Yaman [18], Nehdi and Ladanchuk [19] indicated that micro fibre usages instead of macro one in the concrete mix led to higher compressive strength results. After the high temperature tests at 200, 400, 600, and 800 °C, based on Fig. 2b, all concrete series lost 8%, 17%, 58%, and 79% of their compressive strength in average, respectively.

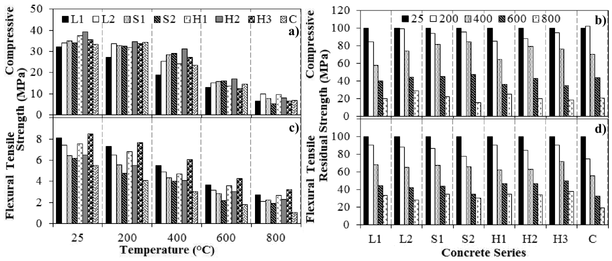

Fig. 2. (a) Real compressive test results of concrete series, (b) residual compressive strength test results of concrete series, (c) real flexural tensile strength test results of concrete series, (d) residual flexural tensile strength test results of concrete series.

The results obtained from flexural tensile strength tests for FRSCLWCs and C for all temperature levels are given in Fig. 2c and d, respectively. In Fig. 2c,d, it is seen that fibre coded as L has the better effect on flexural tensile strength results of FRSCLWCs in single design. Besides, the best results were obtained from the H3 coded hybrid FRSCLWC series including 75%L+25%S fibres. In all concrete groups, the lowest flexural tensile strength value was obtained from the series C. From the results, it was recognised that the decrease of the fibre length and aspect ratio in the single mix design and decrease of the long fibre volume fraction in the hybrid mix design led to dramatical fall of the flexural tensile strength. Nonetheless, series H1 which was hybrid design including 50%L+50%S fibres gave a very close result to series L1 and H3 on flexural tensile test. In Fig. 2c, based on the result obtained from the series L1 and S1, it was observed that 80% and 27% decrease of the fibre length and aspect ratio, respectively, caused nearly 20% drop of flexural tensile strength at 28 days. Besides, when the volume fraction of long fibre (L1 and L2, see Table II) is decreased to 50% in the mix, flexural tensile strength decreased by 10%. This situation is similar for S1 and S2 series, as well.

As mentioned first paragraph, one type fibre using in the mix has caused big fresh properties problems if the used fibre is so long. On the other hand, small fibre usage is giving better fresh properties while it is leading to worse flexural tensile strength properties in hardened situation. These circumstances are not moderate, optimal and desired results in the aspect of fibre reinforced concrete technology. Concrete structure has multiple--phase. Its structure includes calcium–silicate–hydrate (c–s–h) gel in scale of micron and fine/coarse aggregate in scale of millimetre and centimetre. That is the reason why it is not possible to expect improvements in all phases using only one type fibre in concrete structure including complex phases [20].

Thanks to hybrid FRSCLWC design, not only the problems in fresh concrete condition were achieved using together long and small fibres but also strength properties of designed concretes were improved. Figure 1 showed that long fibre using in hybridization decreased fresh properties while strength properties were improved (see also Fig. 2c,d). But, series H3 gave the best flexural tensile strength result in all conditions. Besides, it has moderately good results in the aspect of fresh properties (see Table IV and Fig. 1). It proves that 25% small fibre inclusion developed fresh properties while specifically 75% long fibre adding improved hardened properties. Moreover, 25% small fibre inclusion showed microcrack bridging effect and 75% long fibre adding prevented formation of macrocracks in hardened situation. This collaboration provided the best results on flexural tensile strength tests in all temperature conditions. It is clear from Fig. 2c,d that the worst results were obtained from the series C after heating tests. It lost 81% of its flexural strength after 800 °C. As for the series H3 obtained best results, 61.5% of flexural tensile strength decrease occurred at 800 °C which was the sharpest temperature test and followed by H1 and H2 (64.5% and 65.5%), respectively. These result indications for flexural tensile strength tests were similar for the other high temperature tests if having a close look to Fig. 2d.

4. Conclusion

This study has proved that FRSCLWC has been designed having better strength properties even under high temperatures based on experimental work. In the design process of mixes, fresh concrete properties were affected from the fibre length, aspect ratio, and volume fraction in the concrete mix. Besides, increasing volume fraction of macrofibre in the hybrid design also affected negatively the fresh properties of FRSCLWCs. As a consequence, lower fibre volume fraction and microfibre usage in the single design, and higher microfibre volume fractions usages in the hybrid design led to better fresh properties.

On the contrary, macrofibre usage in the FRSCLWC design showed the lower fresh concrete properties while it was giving better flexural strength properties in hardened condition.

On the other hand, hybrid FRSCLWC design gave the best results both in fresh and hardened situations. In the hybrid design, not only did micro fibre usage lead to improvement of the fresh properties but also helped to macrofibre by bridging the microcrack generations in hardened state. All FRSCLWC series showed relatively similar compressive strength behaviours at the same temperature condition. The decrease of fibre sizes in the usage of single fibres and macrofibre density in the hybrid mix caused a minor increase on compressive strength results. The usage of fly ash in the production of FRSCLWC led to decrease of cement consumption and resulted in more economic and environment friendly FRSCLWC production. On the other hand, returning of that waste material to industry decreased CO_2 emission, as well.

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