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BRITTLENESS OF HIGH-STRENGTH LIGHTWEIGHT AGGREGATE CONCRETE

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Abstract

Modern society and infrastructure are facing an increased demand for fast construction. A number of viaducts are aged and will need to be replaced in near future. When considering this replacement task, lightweight, slender bridge is the solution. Dead load reduction and high-strength to weight ratio are the main advantages when using the lightweight aggregate concrete (LWAC). Still, structural applications of LWAC are lacking. The main disadvantage of LWAC compared to regular concrete, which refrains its wider structural application, is its brittleness and uncontrolled crack propagation, especially when LWAC is exposed to compression. One of the ways to improve brittleness and increase the ductility of concrete is by addition of fibers. In this research, preliminary study is performed where fiber reinforced LWAC mixture was designed and tested. The mix consisted of lightweight aggregate Stalite, leading to high-strength LWAC and polyvinyl alcohol fibers (PVA) providing reduced brittleness and explosive failure. Results on fracture behavior and compressive strength with the increased amount of fibers were investigated and showed promising behavior. In future, structural tests (e.g. compression tests on prisms and beams) will be performed to further verify the benefits of combining aggregate Stalite with PVA fibers for structural applications of high-strength LWAC.

Keywords: Lightweight aggregate concrete, Fibres, Brittleness, Ductility, Slender bridges, Innovative bridge design

1. Introduction

Nowadays, the demand for fast construction increases. A special task is that a majority of the bridges and viaducts are aged and will need to be replaced in the near future. Many countries worldwide face a similar problem and a solution for dealing with it is urgently needed. In this context, new materials and techniques can provide cost-effective solutions thereby minimizing the construction time and reducing the traffic hinder. When considering replacement task high-strength lightweight, slender bridge can be an optimal solution [1].

Lightweight aggregate concrete (LWAC) has been used successfully for structural purposes for many years. The preferable structures are floating offshore platforms, marine structures and bridges [2,3]. The main advantage that classified lightweight concretes as a desired material for use is reduced dead weight of a structure, and in long-span bridges and high-rise buildings, dead load is a significant portion of the design load. By reducing the weight of the structure, lightweight concrete also reduces bearing, substructure and foundation design loads that may contribute to cost savings in the structure. For the projects where seismic events must be considered in design, reduction of weight is especially significant since it lead to reduction in seismic design load [4,5]. Another important application for the reduced density of lightweight concrete is its use for concrete elements that are prefabricated (precast) to facilitate easier handling and faster construction [2]. High strength lightweight aggregate concrete, i.e. having 28-day characteristic compressive strength in the range 60-80 N/mm^2 with oven dry density equal or less than 2000 kg/m^3.
Apart from many foreseen benefits and advantages when using LWAC, structural applications is still lacking. The main reason for that compared to normal weight concrete (NWC) is its brittleness and uncontrolled crack propagation, especially faced when LWAC is exposed to compression. The brittleness of concrete is characterized by sensitivity to stress concentrations and a rapid crack/fracture development. This is attributed to the difference in fracture behaviour of two types of concretes: in regular concrete, cracks are formed around the aggregates, following aggregate-paste interface zone whereas in LWAC cracks propagate through the aggregate. As a result, more tortuous cracking route is made in regular concrete leading to more stable crack propagation and higher fracture energy. For structural analysis, it is essential to know the complete stress-strain curve under uniaxial compression including the descending branch. The main concern for designers when using LWAC is steep and short descending branch, since concrete behave in a brittle manner. Therefore, additional brittleness introduced by LWAC should be certainly avoided. In order to improve this disadvantage of the LWAC concrete, a case study on several LWAC mixes was performed, whereby lightweight aggregate Stalite was combined with polyvinyl alcohol fibers (PVA) [6].

2. Future replacement task

In the past, many cast in-situ reinforced concrete plate bridges were built. The main advantage of this bridges were higher slenderness because of multiple intermediate supports over a single span bridge. At the time when cast in-situ plate bridges were built, the construction time and traffic hindrance was not a serious issue as today. Keeping in mind that many of these bridges and viaducts are constructed for a design service life of 50 years, the replacement is needed. Nowadays, with expansion of the road network and serious implications due to traffic hindrance, the main replacement requirements become more demanding. Rebuilding of cast in-situ plate bridges is due to its impact on traffic, undesirable solution and should be avoided. In this context, new materials and techniques can provide cost-effective solutions thereby minimizing the construction time and reducing the traffic hinder. The main requirements for the replacement of the existing structures are: to keep the same traffic profile without additional ground work, to minimize the work on existing foundations and to ease transportation during the construction process and provide joining of separate elements of the bridge. Having in mind all aspects mentioned above, high-strength lightweight, slender bridge can be an optimal solution. With this type of bridge it is possible to keep or reduce bridge height, where traffic profile stays the same of increase. Using of the

prefabricated LWAC box girders reduce the weight of concrete elements, making the use of precast elements more feasible by reducing requirements for shipping, handling and erection. In addition traffic impact is reduced to a minimum during construction time.

3. Case study - LWAC with fibres

3.1 Lightweight aggregate concrete (LWAC)

Structural lightweight aggregate concrete is made when normal weight aggregate (NWA) is replaced with lightweight aggregate (LWA). That is simply lighter a rock, produced using shale, clay or slate, so the same batching and admixtures are used for preparation of lightweight aggregate concrete like the same procedures and equipment as a for conventional concrete. Typical LWAC mixtures that use coarse LWA and conventional sand have a oven-dry density of 1750 to 2000 kg/m3, followed by compressive strength up to 70 MPa (based on cylinder strength). Water absorption of LWA is higher than the absorption of NWA, in the range from 6 % to 25 %. Because LWA has a higher absorption, lightweight concrete typically loses mass with time as excess absorbed water migrates out of the concrete. The oven-dry density as the density achieved after moisture loss has occurred is used for design criteria. As a result of lower density of aggregate, density of LWAC is reduced in range from 25-30% compared with NWA. That is significant in areas where dead load is one of the largest determinative factor, especially in seismic areas. This feature allows the reduction of cross sections, improve structural efficiency and economy.

Density of the LWA is lower than density of the cementitious paste, which require extra care during the production of LWAC. Control of absorption and moisture during production is necessary to produce concrete with consistent properties. LWAC generally requires more cementitious material and lower water-cement (w/c) ratio to achieve higher compressive strength. The porous nature of lightweight aggregate reduces its stiffness. In hardened LWAC, strength and rigidity of the aggregate is lower than that of the paste, leading to crack distribution through aggregate, lower strength development and lower ductility. As a result of that phenomena, fracture energy, tensile strength and E-modulus are lower for LWAC [2-5]. In addition, LWAC have brittle nature, uncontrolled crack/fracture development followed by an explosive failure. Together with the main stress-strain curve under uniaxial compression, where the descending branch is steep and short, this is main concern for the designers when using LWAC as preferable material. One of advantages when using lightweight concrete is improved fire resistance. This feature is significant for building construction where structural elements are often required to provide a certain resistance to fire exposure. The insulating properties of lightweight concrete allow a smaller (and also lighter) thickness of concrete to provide the same resistance as for NWA [2,5]. The significant benefit with respect to durability when using the lightweight concrete is reduced shrinkage. This is provided due to internal curing from the water that is absorbed and stored in aggregate itself [5].

3.2 Tensile strength and shear capacity of LWAC with Stalite as aggregate

Previous experimental investigation dealt with the tension behaviour of LWAC with Stalite as aggregate. Behaviour and ductility of beams with and without shear reinforcement were observed in 4-point bending test. The main test parameters that were varied in those tests were the shear span length to effective height ratio (a/d) and amount of shear reinforcement. All the tested beams showed ductile behaviour because they were able to withstand significant

increase of load after formation of shear splitting cracks. Crack formation in the tested beams were similar as for normal weight concrete. By qualitative visual inspection for all the tested beams without shear reinforcement it was observed explosive, loud and brittle failure [7]. When observing the cracked area, propagation of cracks goes through and around LWA, leading to higher tensile strength and fracture energy [5,7]. High-strength LWAC with Stalite as aggregate showed promising behaviour.

3.3 Polyvinyl alcohol fibres (PVA)

Polyvinyl alcohol fibers (PVA) is mostly use to improve the inherent brittleness of cementitious materials and to control cracking. They have very little effect on the flexural strength and deflection capacity. The compressive capacity is slightly reduced while concrete surface of the elements become extremely ductile [8].

3.4 Experimental program, results and discussion

Small experimental program have been created in order to create non brittle and ductile high-strength LWAC. The main concern was to deal with brittleness, explosive failure and to improve ductility of LWAC. Because of that PVA fibres was introduced in range 0.5 to 1 % at volume fractions. PVA was type "Kuralon RSC15", 8 mm long with E-modul of 36 MPa. All the concrete mixes have been prepared from the same batch of LWA Stalite, argillite slate from North Carolina.

Table 1: Concrete mix compositions (kg/m3) and fresh concrete properties.

Constituent	**LWAC65**	**FLWAC65 with 0.5 % fibres**	**FLWAC65* with 0.5 % fibres**	**FLWAC65 with 1% fibres**
Cement (Norcem Anlegg FA)	431.1	414.4	397.5	435.5
Silica fume (Elkem Microsilica)	22.7	21.8	20.9	22.9
Water (free)	177	170.1	163.2	206.3
Absorbed water *sand+aggregate	53.6	49.3	46.7	45.6
Sand (Ramlo 0-8 mm)	552.6	559.1	531	517.5
Sand (Ramlo 0-2 mm)	236.8	239.6	377.3	221.8
Aggregate (Stalite ½″)	530.5	536.72	493	496.8
Superplasticizer (Mapei Dynamon SR-N)	5.4	5.1	6.2	6
Synthetic fibres (% of volume)	-	6.5	6.5	13
Fresh concrete properties				
Matrix volume [l/m^3]	360	360	360	400
Slump [mm]	240	35	40	10
Fresh density [kg/m^3]	2013	1900	2011	1663

Stalite was completely saturated to avoid water exhaustion from the paste and in addition have been controlled moisture and absorption of the aggregate just before the mix preparation. One concrete mix (LWAC 65) was prepared as a reference one without addition of the fibres, while three mixes contain fibres. Tab. 1 shows all the concrete mixes and fresh concrete characteristics. All the mixes have been prepared in laboratory controlled conditions, in a mixer with vertical pedals and capacity 25 liters. In order to provide good distribution of the fibres in FLWAC, first was prepared paste where were added fibres and later was introduced aggregate with continuous mixing. From the LWAC and FLWAC mixes have been casted several cubes and cylinders for the testing and following of compressive strength at 7, 14, 28, 38 and 46 days. At age of 28 days cylinders from all the prepared concretes were tested under compression to get E modulus [9]. From that test it was plotted stress-strain diagram, see Fig. 1. It can be noticed that LWAC65 showed brittle behaviour, when failure happened load immediately failed down, while all other mixes with fibres showed ductile behaviour with very smooth peak load where load goes slowly down and samples can sustain additional loading .

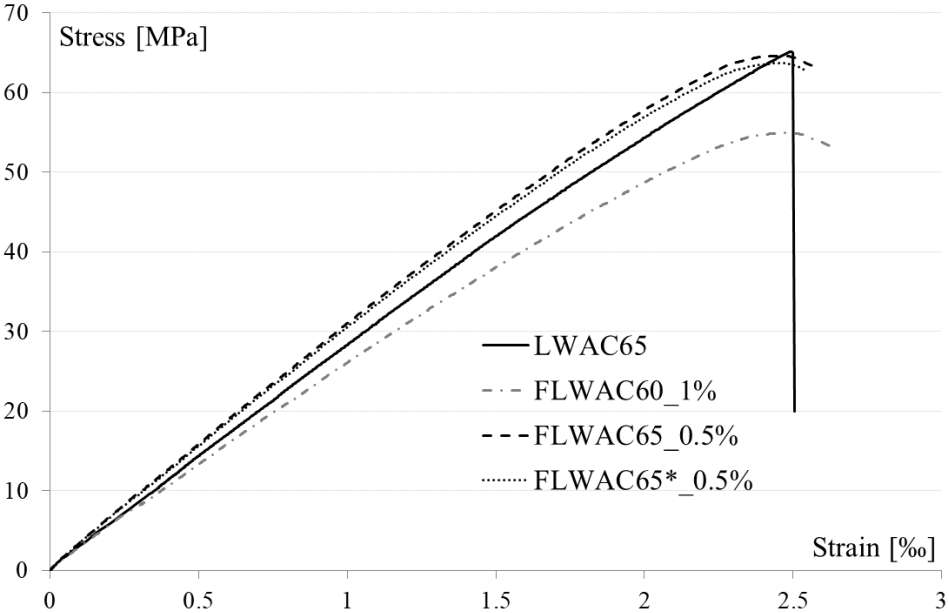

Figure 1: Stress-strain diagram for all the tested mixes at age 28 days

When testing lightweight aggregate concretes it was noticed that by adding the fibres, even in small amounts, workability of the concrete mix was significantly reduced. Concrete like this is very tough to cast, especially in sections that contain a lot of reinforcement is tough to embed this concrete. Mix FLWAC 65* contain more fine sand, fraction 0-2mm, in order to provide more stable paste and concrete, but still workability was very low. That happens because fibres arrest water which is wrapped around them. From the other side through qualitative visual inspection of the fracture, all tree FLWAC concretes did not showed any brittleness and explosive failure compared to LWAC 65. It was surprising that all the FLWAC cubes and cylinders kept together afterwards and can sustain additional loading. By adding the fibres in amount of 0.5% compressive strength is very slightly reduced while effect on the brittleness is the same like for mix with 1% of the fibres. For the FLWAC mix that contain 1% of the fibres compressive strength is significantly reduced, almost 18%.

4. Conclusions

When using the LWAC the weight of the structure can be reduced for the 25-30 %. Having this in mind, like all the other mentioned advantages, LAWC seems to be a promising material for any structural applications, especially for the replacement bridge task. By introducing a small amount of PVA fibres, just 0.5%, the lightweight concrete became non brittle and without an explosive behaviour. In addition small amount of fibres did not influenced the compressive strength of concrete. In the future, structural tests (e.g. compression tests on prisms and beams) will be performed to further verify the benefits of combining aggregate Stalite with PVA fibers for structural applications of high-strength LWAC.

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