Vol.23 No.01
Jan, 2024
MATERIAL SCIENCE AND TECHNOLOGY
DOI:10.10543/f0299.2024.41905

EXPERIMENTAL INVESTIGATIONS ON HYBRID FIBER REINFORCED SELF-COMPACTING LIGHT WEIGHT CONCRETE

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Abstract: This research aims to investigate the effects of two commonly used fiber types and lightweight porous perlite aggregate on the mechanical and physical characteristics, frost durability, and microstructure of self-compacting lightweight concrete (SCLC). Tests on cubes and prismatic samples of SCLC and fiber-reinforced SCLC with varying contents ranging from 0.5 to 1% of basalt fibers (BF) and/or 0.5% of steel fibers (SF) comprised the experimental inquiry. Two different fine perlite aggregate contents—5% and 15%—were employed in this investigation. Workability in fresh state SCLCs (slump-flow and t500 values) has been completed. Numerous data were collected and analyzed regarding frost resistance, the microstructure, including the interfacial transition zone (ITZ), and compressive and flexural tensile strength in bending behavior. In comparison to SCLC without fibers, the hybrid fiber-reinforced SCLC with perlite aggregate exhibited a more ductile behavior. During a test of flexural tensile strength, fibers span fractures. Porous SCLC was effectively shielded from frost assault by BF, whereas SF was damaged.

Keywords: self-compacting concrete; basalt fibre; steel fibre; perlite; frost resistance; microstructuremechanical properties; interfacial transition zone

1. Introduction

An rising number of research on the subject [1–5] indicates that self-compacting concrete (SCC) has garnered attention in recent years. Because of its exceptional flowability and resistance to segregation, SCC may completely enclose the reinforcing parts inside the mold without experiencing mechanical compaction [4,6, 7]. Reducing the water/binder ratio, increasing the volume of cement paste, regulating the total volume of coarse-grained aggregate, regulating its maximum grain size, and applying high-quality superplasticizer with multiple admixtures modifying viscosity in order to ensure balance between formability and stability are some of the guidelines that were determined for the SCC design [6–9]. A self-compacting concrete mixture should have a workability that is sufficiently stable for transportation and concreting, a relatively low yield strength, and an average viscosity that provides the right resistance to bleeding and segregation. As there is no longer a requirement for mixing vibration, SCC has several advantages over regular concrete, including a reduction in construction time, labor, equipment utilization, and noise at building sites [8]. Additionally, SCCs with lightweight aggregates (LWA), like Pollytag, are becoming more and more common. According to Kaszyn´ska, M. and Zielin´ski, A. [10–12], LWA permits interior cure by the progressive release of water from presaturated LWA, balancing interior moisture content. Rubber granules [13], lightweight expanded clay aggregates [14], sugarcane bagasse ash [4], oil-palm-boiler clinker (OPBC)—a solid waste from the oil palm industry [15]—pumice, volcanic tuff, and diatomite, as well as recycled modified polypropylene (PP) plastic particles—are just a few of the lightweight aggregates that SCLC uses. According to Yang, S. et al., a higher plastic content results in less slump loss and an improvement in slump flow value. When plastic replaces sand to a very small extent (20%), the penetration through concrete.

Aslani, F. spoke on the recommendation to apply different kinds of fibers in SCC. To reduce cracking and increase the material's overall ductility, fibers are incorporated into the matrix as reinforcement. According to published research, basalt fibers (BF) are used in concrete to strengthen cement matrices because of their unique features, which include increased strength, durability, stability, and resistance to repeated impacts [4]. The flexural and tensile strength, ductility, and cracking energy of cement materials are all enhanced by the addition of basalt fibers to mortars. According to Ralegaonkar, R. et al., the effective addition of basalt fibers is around 1-3 percent (w/w) of binder. When basalt fibers are added to mortar, the drying shrinkage is decreased and the mortar's resistance to cold, abrasion, and alkali is greatly increased. The authors have mentioned in prior papers that the fibers often improve porosity and absorptivity. Steel fiber (SF) is another form of fiber that is widely used in a variety of applications. SF has been shown in several tests to effectively reduce the likelihood of cracks and scratches in concrete, and consequently in structures. Concrete's tensile, flexural, and dynamic modulus of elasticity are all enhanced by the addition of SF, while its compressive strength is negligibly affected. According to Smarzewski, P. and Barnat-Hunek, D., concrete containing SF has a relatively poor frost resistance; this resistance is also dependent on the concrete's porosity, aggregate, and fiber characteristics, as well as the surrounding environment. According to Gao, D. et al., mortar should be applied to the steel fiber surface to guarantee that the concrete reinforced with steel fibers is of a sufficient quality and resistant to corrosion.

The degree of water saturation, the configuration of the pores in the hardened cement paste, and the kind of aggregate utilized determine how resistant concrete is to the freezing-thawing (F-T) phenomena. The fundamental attributes of concrete with strong freezing-thawing resistance are limited permeability and low water/binder ratio. There aren't many research on the behavior of cement-based composites, namely fiber-reinforced concrete, during freezing and thawing. This is particularly true for SCLS reinforced with hybrid fibers, as no study has been done on this subject to the best of our knowledge.

Generally speaking, frost damage or shrinkage in hardened concrete are two common causes of fractures in concrete. These fractures cause concrete's waterproofing qualities to deteriorate and expose its microstructure to dangerous elements and compounds including sulphites, chlorides, and moisture. Because lightweight concretes are weaker and less resistant to cold than regular or high-performance concretes, cracks are more likely to occur in them. The application of fibers with varying lengths and qualities is a useful way to address this problem since these fissures, which may occur in concrete floors constructed with self-compacting concrete as well, manifest themselves in a variety of sizes and stages of exploitation. Controlling fractures of varying sizes in different concrete zones is the primary goal of integrating different types of fibers.

As far as we know, there hasn't been any research done on the microstructure of hybrid fiber-reinforced SCC with light aggregates like perlite to see how it affects the wettability, strength, and resistance to frost of these unique concretes. Therefore, a unique microstructure-properties connection was used to determine these parameters. The goal of the scanning microscopy study on the microstructure hybrid fibers-reinforced SCCs with lightweight perlite aggregate was to identify the varied geometrical microstructure of the SCCs under consideration, which contains BF and SF and has a major impact on their mechanical and physical characteristics, particularly their resistance to frost. Self-compacting concrete can be used to create building parts when its features are desired, such as self-compacting industrial flooring, by simultaneously applying a combination of fibers and perlite.

2. Materials and Methods

2.1. Materials

Portland cement with CEM I 42.5 R was used to prepare the concrete. Through the preparation of several test batches, the ideal water/binder ratio and concrete content were ascertained through experimentation. For the creation of the mixes, washed quartz sand, 2–8 mm granite aggregate, perlite (replacing 5% and 15% of the sand), and micro-silica were used. In two mixes, C5P0 and C15P0, basalt fibers (BF) and steel fibers (SF) were not added; in C5P1b and C15P1b mixtures, 1% BF admixture was used; in C5P50b50s and C15P50b50s, 0.5% SF and BF addition was used. Different components were also present in perlite (0/2 mm), an acidic sodium-potassium aluminosilicate that was hydrated and had a density of 95 kg·m−3. Silica SiO_2 (65–75%), aluminum, sodium, potassium, magnesium, calcium, and iron oxides [Al_2O_3 (10–18%), $K_2O + Na_2O$ (6–9%), $MgO + CaO$ (2–6%), and Fe_2O_3 (1–5%)] made up the majority of its composition. Perlite has a water absorptivity of three to five percent. Abrasion resistance (6050 mm3/5000 mm2), compressive strength (190 MPa), flexural strength (11.5 MPa), open porosity (0.95%), water absorption (0.35%), and apparent density (2650 kg·m−3) were the characteristics of granite aggregate (2–8 mm). The specified dimensions of the used SF were 50 mm in length, 1000 μm in diameter, 7800 kg·m−3, 1100 MPa tensile strength, and 200 GPa elastic modulus. The specific surface area of the powdered silica fume was 15–30 m2·g−1. The spherical molecules found in silica fume are far smaller than those found in cement. It is more reactive because to its larger surface area, which also guarantees a high early strength growth, low concrete permeability, and a decreased chance of bleeding. The following were the main ingredients of the commercial silica fume utilized in this investigation: 96% of the weight is SiO2, 1% is CaO, and the specific gravity is 2170 kg/m−3. The specific gravity of quartz sand (0/2 mm) is 2650 kg·m−3, its water absorption is 1.2%, and its moisture content is 0.16%.

2.2. Methods

After two minutes of mixing all the ingredients except BF and SF, BF and/or SF were added. Water was added and stirred for a further two minutes after that. After examining the concrete mixes, half of the molds were filled, and the molds were compressed for one minute on a vibrating table. After that, samples were crushed once again and a second layer of mixes was applied. After being kept in the lab for twenty-four hours, the samples were taken out of the mold and left in water at a temperature of twenty-two ± 2 ◦C for seven and twenty-eight days.

2.2.1. Research Characteristics of Concrete Mixtures

As per the PN-EN 12350-8:2012 standard, a slump-flow test and an evaluation of viscosity class t500 were used to analyze the workability. A 900 mm by 900 mm stainless steel plate with a smooth, flat surface was positioned in the center of an Abrams cone. Subsequently, the cone was filled without mixing or compacting the concrete so that it did not leak from the bottom. It evened out the surplus on top. The cone was firmly raised upward after a maximum of thirty seconds (1-3 s). Time t500 was precisely recorded at intervals of 0.1 seconds after the cone started to separate from the plate, until the mixture reached a diameter of 500 mm. The flow diameter was then measured in two perpendicular dimensions and rounded to the nearest 10 mm. Following the slump-flow test, the stability of the concrete mixture was evaluated. It entailed examining an equal distribution of the aggregate and determining if the mixture patch's circle displayed evident segregation in the form of a slurry film or water. The question of whether the coarse-grained aggregate gathered in the mixing patch's center attracted attention. Using the pressure method, the air content of the concrete mixture was determined in accordance with PN-EN 12350-7 standard.

2.2.2. Research Characteristics of Hardened Concrete

Six cubic samples of each concrete, each having an edge length of 100 mm, were made in order to assess the physical characteristics. They were employed in the investigation of water absorption by weight, porosity, frost resistance, and volumetric density. Regarding the mechanical characteristics, a total of 12 cubic samples measuring 100 mm in the edge were prepared for the compressive strength test (6 samples were tested after 28 days of maturation, and the remaining 6 samples after 7 days), and an additional 12 cubic samples of the same size were used for the frost resistance test. Six 100 mm × 100 mm × 500 mm cuboid samples were used to evaluate the flexural tensile strength.

The samples used in the weight test for water absorption were positioned on a 10 mm grate that was hung above the bathtub's bottom and immersed in water up to their height. The water level was raised to 10 mm above the samples after a 24-hour period. After a further twenty-four hours, the samples were taken out, cleaned, and weighed. The concrete samples remained wet for so long that there was no mass growth seen in the next two weightings. Following saturation, the samples were dried to a consistent mass and weighed. The volumetric density of the concrete and its water absorption by weight were then calculated using the PN-B-06250:1988 standard. Using the AutoPore IV 9520 (Micrometrics, GA, USA) tool, the porosity of concretes was investigated using the Mercury Injection Capillary Pressure (MICP) method. Sidney D. and Rigby SP et al. described the measuring technique. It makes it possible to examine pores that have widths between 3 nm and 200 μm. The sample's surface area was around 1 cm2, and it was dry since the injection of mercury is impeded by the presence of other liquids. Similar to water absorption tests, the frost resistance test was conducted on cubic samples after 28 days of maturity. Samples were soaked in water before the test was conducted. For four hours, freezing was done at a temperature of -20 ◦C.

The samples were then allowed to defrost for four hours in water that had been heated to +20 ◦C. In accordance with PN-B-06250:1988, the weight loss of the samples and a drop in compressive strength relative to the reference samples maintained in water at a temperature of +20 ◦C ± 2 ◦C during the experiment were assessed. As per the PN-EN 12390-5 standard, cuboid samples were used to evaluate the flexural tensile strength. The samples were put in a universal testing machine and a three-point flex test was performed as part of the investigation. After noting the maximum load, the flexural tensile strength was computed. Each produced concrete sample was used for the experiment after it had matured for 28 days. In compliance with the PN-EN 12390-3 standard, cubic samples with an edge length of 100 mm were subjected to the flexural tensile strength test. To ascertain the shape and microstructure of concrete, scanning electron microscopy (SEM) was utilized, utilizing a Quanta FEG 250 microscope manufactured by FEI in Hillsboro, OR, USA. Carbon adhesive was used to attach the samples for the SEM investigations on a carbon holder. They were then coated in a coating machine with a 50 nm thick layer of carbon to give the sample's surface conductivity. The process of preparing the samples eliminates the chance of surface cracks and other micro-defects in the concrete. Low vacuum and low beam energy were used to eliminate the chance of further surface flaws.

3. Results & Discussion

3.1. Properties of Concrete Mixtures

Not a single blend under study displayed any bleeding or other segregation-related symptoms. The SCLC without fibers has a value of 750 mm, whereas the SCLC with 1% BF has a value of 660 and 680 mm. This difference allows for the achievement of the SF2 needed for SCC [13]. Slump-flow measurements for the SCLC did not all fall within the recommended range of 600–700 mm. Blends utilizing hybrid fibers were able to attain the SF1 class and a 550–600 mm flow diameter. It was found that the fibers compress the mixture, which lowers the mixed solids (SF) class. Fibres impede the spread of the mixture, particularly steel fibers which have notable length and thickness. This is mostly due to the elongated shape of the SF utilized in the test, which may adversely affect the fluidity of fresh SCLC and cause the flow time t500 to increase by more than double. When the sand replacement was raised from 5% to 15%, the viscosity rose. BF was added next, and then BF and SF were added at the same time. The combinations including hybrid fibers (C5P50b50s and C15P50b50s) had the lowest SFmax and the maximum viscosity. These combinations also have the largest air content—6.0 and 6.2%, respectively—while the mixture with the least amount of perlite and no fibers (C5P0) only manages 2.6%. Research has shown that fibers impede the mixture's ability to self-compact and deaerate. To provide enough flow and offset the workability decline, it may be necessary to increase the superplasticizer dosage. However, due to the greater quantity of superplasticizer and more porous nature of lightweight aggregates, care should be taken while working with mixes containing these types of aggregates since they are prone to segregation.

3.2. Properties of Hybrid Fibres-Reinforced Self-Compacting Lightweight Concrete

Only the C5P0 concrete was shown to be ineligible for classification as lightweight concrete based on volumetric density (lightweight aggregate volumetric density is limited by the standard to 2000 kg/m3). This is caused by the combination having the least quantity of air in it as well as the use of just one additive—perlite—in a level less than 5%. The findings regarding water absorptivity demonstrate a distinct impact from both the inclusion of porous perlite (as the obtained values are substantially greater than those for regular concrete) and the application of fibers, particularly steel ones, which increases the porosity of mixes. In general, lower values were obtained when analyzing the compressive strength test results in the concretes containing 15% perlite, independent of the kind of other added additives. This is particularly relevant to the first strength levels following seven days of development. After 28 days of maturity, there is less of a difference between the compressive strength values of the C5P and C15P concretes. After seven days for the C5P concrete to mature, the 1% addition of BF resulted in a 68% drop in strength, while the additions of BF and BS generated a 37% reduction in strength relative to the C5P0 strength. C15P0 concrete's strength was lowered by 29% and 77%, respectively. The concrete structure's weakening due to the increasing inclusion of porous perlite, which has poor strength properties, is linked to the observed decrease in C15P concrete's strength.

Greater open porosity in the hardened concretes and twice as high an air content in these mixtures should be linked to lower strength fiber-reinforced concretes. The Interfacial Transition Zone (ITZ) structure between the fibers and cement slurry is also linked to the lowest strength values found in the concretes that had BF added to them. Between SF and cement slurry, the ITZ is noticeably superior. The findings of microstructural examinations, which were detailed and clarified in Section 3.3, supported this.

Perlite and fiber addition have differing effects on flexural tensile strength. Elevating the perlite content from 5% to 15% lowers the concrete's flexural and compressive strengths. However, things change when you take into account just the impact of BF and BS addition. The flexural strength is decreased by 27% when compared to C5P0 and 34% when compared to C15P0 with the single BF addition. Nevertheless, the flexural strength increases—by 5% for C5P50b50s and 6% for C15P50b50s, relative to C5P0 and C15P0, respectively—if a blend of fibers comprising 0.5% BF + 0.5% BS is used.

The composition of the concrete, its absorptivity, porosity, content, and kind of fibers all affect how vulnerable SCLC is to freezing and thawing-related damage. In contrast, it is challenging to clearly show a connection between mass loss and strength decline based on the findings of the frost resistance test. It appears that the addition of perlite, which lowers the frost resistance, has the greatest effect on this parameter. The inclusion of BF resulted in an improvement for both C5P1b and C15P1b. The use of SF and BF together did not provide results that were good enough. But only C15P0's concrete failed to fulfill the standards, with a mass loss of 7.88% and a limit value of 5% in accordance with the PN-B-06250:1988 standard. The remaining outcomes fall within the range of acceptable values.

The thawing water moves into cavities along with the volume increase. According to Fagerlund, this technique helps to raise the hydraulic pressure. Microcracks start to show up when the expanding force is greater than the concrete's tensile strength. More water seeps into concrete and the freezing and thawing cycles inflict more severe damages when the cracking process begins and the structure of SCLC with fibers is further damaged. The P15P0 concrete with the highest quantity of perlite and no fibers showed the most mass loss (7.8%) and compressive strength drop (8.1%). The sample damage may have occurred because of the lightweight aggregate content, which lowers the tightness of the concrete.

As anticipated, a large amount of concrete damage happened in the hybrid fiber-reinforced SCLC as the quantity of steel fibers grew during periodic freezing and thawing. Throughout the experiment, the surface of the C15P50b50s concrete samples developed several fractures and loosening in the concrete along with SF corrosion. The primary cause of the expanding internal pressure in concrete with SF during the freezing of water is the increased quantity and number of capillary pores and voids between steel and slurry. According to studies, steel fibers did not prevent failure during T-F cycles by delaying the onset of microcracks. A publication revealed similar results in UHPC concrete. Afroughsabet, V., and Ozbakkaloglu, T.'s work demonstrated the beneficial effects of hybrid fibers during 100 cycles of freezing and thawing very durable concrete, both with and without steel and polypropylene fibers. Concretes without fibers saw decreases in their flexural strength, compressive strength, and dynamic modulus of elasticity of 23%, 14%, and 9%, respectively; in contrast, concretes reinforced with fibers saw decreases in these parameters of 12%, 10%, and 8%. Unlike SF, the basalt fibers in our research effectively shielded SCLS from the effects of cold. Even though SCLC with BF has more porosity and absorptivity, the small, thin fibers fill in fractures and scratches and shield the concrete from frost damage. Frost-related losses are 70 times less in concrete with a 5% perlite content and nearly 6 times less in concrete with a 15% perlite concentration.

3.3. Microstructure of Hybrid Fibres-Reinforced Self-Compacting Lightweight Concrete

The samples from the unaltered cuboids utilized for the tensile strength testing—the pieces that were not exposed to stresses—were used for the microstructural studies of SCLC. ITZ has a significant influence on the mechanical characteristics of concrete as it is the weakest part of the material and where microcracks initially appear. Due to perlite's porous nature and its intense absorption of water from the cement paste, lightweight concrete has a different ITZ than regular concrete. The thickness of ITZ is significantly influenced by the amount of water present in the mixture. There is a C-S-H layer and a layer of aligned portlandite crystals directly on the surface of the granite aggregate. The adhesion between the cement matrix and rough perlite aggregate determines the structure and ITZ characteristics of the concretes under analysis. Regarding the granite aggregate, there was extremely high adhesion between the cement paste and perlite aggregate. The surface roughness of crushed granite aggregate affects the bonding between granite and cement paste, which is weaker than the bonding between perlite and cement paste. Grain breaks are glassy and conchoidal. Observations showing 2–5 µm fissures between the cement paste and granite aggregate supported this conclusion. But in certain places, the cement paste and steel appear to be unbonded, leaving empty spaces in between. Cement paste showed only a poor adherence to BF in the concretes containing BF. The smooth, slippery, hydrophobic surface of BF makes it difficult for these two materials to bind. Increased slick BF content results in more free water around BF, which weakens the binding between BF and cement paste and leads to the formation of fissures, void-filled zones, and relatively poor adhesion. Similar findings were reported in the Yang, S. et al. publication, however they dealt with the cement paste's adherence and the plastic aggregate's smooth surface. However, the frost resistance remained intact despite this circumstance. To effectively protect SCLC from frost attack, cement paste adherence to BF is adequate.

The construction is tight and there are no obvious fractures or scratches in the case of concrete without fiber addition. Conversely, in fiber-containing SCLC, a large number of air holes and fractures with diameters varying from 0.1 to 0.55 mm are present. As demonstrated by the research conducted by other authors and reported in the study (26), fiber-reinforced concretes exhibit higher porosity and absorptivity as well as significantly lower compressive strength when compared to concretes without fibers. The authors demonstrated that the frost resistance and compressive strength of cement mortars are adversely affected when BF is added. Porosity can grow by up to 32% in tandem with a rise in BF. The authors found that, in contrast to SCLC, cement paste adhered to BF extremely well and that the C-S-H phases had crystallized in the cement mortars.

About 20% of the hardened cement slurry made from Portland cement is calcium hydroxide, along with calcium aluminoferrite and aluminate hydration products. The other 70% of the slurry is made up of hydrated calcium silicates, namely the C-S-H phases. Short fibers or hydrated calcium silicate phases fill the pores of the hardened cement paste during the third hydration phase. The conversion of calcium aluminate trisulfate $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ to calcium aluminate monosulfate $3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$ is the phase's defining property.

4. Conclusions

The investigation into the potential uses of SF, BF, and perlite aggregate demonstrated their viability in the manufacturing of building materials like SCLC. A thorough analysis of the obtained results enables to formulate the following conclusions:

Fibre-reinforced concretes, both with basalt and steel fibres, are characterised with greater porosity and absorptivity as well as much lower compressive strength in relation to the concretes without fibres addition. The lowest strength values were obtained for the concretes with BF addition. Microstructural studies showed that this is connected with the ITZ structure between fibres and cement slurry. Adding BF alone reduces the flexural strength by 27% in relation to C5P0 and by 34% compared to C15P0. However, if a combination of fibres involving 0.5% BF + 0.5% BS is applied, then the flexural strength improves—by 5% in C5P50b50s and by 6% in C15P50b50s, in relation to C5P0 and C15P0, respectively. As the addition of perlite increases, the absorptivity and frost resistance of considered concretes deteriorates. An improvement in frost resistance can be achieved by the application of BF in the amount of 1%. Utilising a combination of basalt and steel fibres no longer yields satisfactory results. The content of steel fibres significantly influences the increase in the air content within the concrete mixture, regardless of the perlite content. The air content in the mixture with steel and basalt fibres is 8% higher than in the mixture with basalt fibres, on average. The microstructural studies showed a much better ITZ structure of cement paste with perlite aggregate in relation to the granite aggregate. In turn, the ITZ between cement paste and fibres depends on their type. The cement paste exhibits good bonding with the steel fibres, there were no micro-cracks or micro-fractures. The ITZ between SF and cement slurry is significantly better than in the case of BF.

The highest frost resistance was observed in the case of SCLC, which contain basalt fibres, rather than SF. Despite an increased porosity and absorptivity of SCLC with BF, thin fibres bridge cracks, protecting the concrete against frost damage; therefore, in the case of concrete intended for outdoor applications, the C5P1b concrete is recommended. In cases when concrete is to be applied indoors and the resistance to F-T cycles is not necessary, the

SCLC concrete with the highest strength parameters, i.e., C5P50b50s is recommended.

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