Contribution of strain-hardening cementitious composites (SHCC) to shear resistance in hybrid reinforced concrete beams

Luković, Mladena; Budnik, Mladena; Dragaš, Jelena ; Carević, Vedran; Ignjatović, Ivan

DOI
10.5937/GRMK2300006L

Publication date
2023

Document Version
Final published version

Published in
Gradevinski Materijali i Konstrukcije

Citation (APA)
Luković, M., Budnik, M., Dragaš, J., Carević, V., & Ignjatović, I. (2023). Contribution of strain-hardening cementitious composites (SHCC) to shear resistance in hybrid reinforced concrete beams. *Gradevinski Materijali i Konstrukcije*, *66*(3), 145-155. https://doi.org/10.5937/GRMK2300006L

Građevinski materijali i konstrukcije
Building Materials and Structures
journal homepage: www.dimk.rs

https://doi.org/10.5937/GRMK2300006L UDK: 691.328.42
620.17:691.32

Review paper

Contribution of strain-hardening cementitious composites (SHCC) to shear resistance in hybrid reinforced concrete beams

Mladena Luković[1)], Bartosz Budnik[1)], Jelena Dragaš[2)], Vedran Carević[2)], Ivan Ignjatović[2)*]

[1)] Delft University of Technology, Postbus 5, 2600 AA Delft, The Netherlands
[2)] University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia

Article history

Received: 24 April 2023
Received in revised form:
14 June 2023
Accepted: 15 June 2023
Available online: 03 July 2023

Keywords

strain hardening cementitious composite,
hybrid beam,
ductility,
crack,
shrinkage

ABSTRACT

Strain Hardening Cementitious Composite (SHCC) is an innovative type of fibre-reinforced cement-based composite that has superior tensile properties. Because of this, it holds the potential to enhance the shear capacity of reinforced concrete (RC) beams, if applied properly. This paper presents the general and distinctive properties of SHCC as well as a literature review of topics related to the contribution of SHCC layers to the shear resistance of RC beams with and without shear reinforcement. Based on the analysed results, it is concluded that the main characteristics of SHCC are its microcracking behaviour, high ductility, and increased tensile strength (between 2 and 8 MPa) at large deformations. When used in structural elements, SHCC develops multiple parallel cracks compared to concentrated cracks in conventionally reinforced concrete. The biggest disadvantage of SHCC is its significant drying shrinkage. Although showing high variability, using SHCC as laminates with a thickness of 10 mm improves the shear capacity of hybrid RC beams, but debonding of interfaces in a hybrid system occurrs in some cases.

1 Introduction

Concrete is the go-to material for construction due to its affordability, versatility, and ease of use [1, 2]. However, even well-designed concrete structures require regular maintenance and assessment to reach their expected lifespan. Durability issues can lead to costly repairs [3], which is a concern in the era of sustainability and the circular economy. While low cost and versatility have been the driving factors for concrete's dominance, sustainable development will most likely drive our economy in the future [2]. Hence, the sustainability of construction materials will become increasingly prominent.

In order to address the challenges faced by traditional construction materials, it is necessary to explore novel materials that offer greater benefits. One such innovative material is the Strain-Hardening Cementitious Composite (SHCC), which is a special type of cement-based composite reinforced with fibres. SHCC exhibits superior crack control ability under tension [4], thanks to the fibres that bridge cracks at high ultimate tensile strain, giving it an edge over traditional concrete. Consequently, SHCC can lead to improved durability [5] that can potentially outlast that of NC.

Still, the high cost and environmental burden of SHCC make it impractical for use as the sole construction material [6,7]. A more viable solution would be to use a hybrid system that combines SHCC and traditional concrete. By doing so, the material can be used more efficiently, reducing the burden on the environment and keeping its costs competitive. One possible method is to place SHCC in the outer layers of a conventional reinforced concrete (RC) beam, thus utilizing its superior mechanical properties and potentially reducing the need for reinforcement. U-shape shells made of SHCC can be prefabricated in a concrete element factory and used as formwork for cast-in-situ concrete, which can further reduce costs. This hybrid system offers a more sustainable and economical option for construction projects.

Previous research has explored the impact of using hybrid systems with outer layers of SHCC. An experimental study on the flexural and cracking behaviour of reinforced SHCC layers in the tension zone of RC beams was conducted [5] . It was found that hybrid systems exhibit superior cracking behaviour and smaller crack widths compared to conventional RC beams. In the follow-up study, it was shown that the choice of interface property and fibre type can affect the controlled micro-cracking behaviour and resulting cracking pattern of beams. Further research on this topic is available in [8]. On the other hand, only limited experimental research on the shear behaviour of hybrid

---

[*] Corresponding author:
E-mail address: ivani@imk.grf.bg.ac.rs

systems is present in the literature. Although it was numerically shown that when applied monolithically, reinforced SHCC can have increased shear capacity compared to the reference, conventional reinforced concrete [9], it is not clear if the benefits will be preserved in the hybrid system where SHCC and traditional concrete have to work together to bridge the critical shear crack.

This paper presents the general and distinctive properties of SHCC as well as a literature review of topics related to the contribution of SHCC layers to the shear capacity of RC beams with and without shear reinforcement. Shear failure in concrete members or structures is classified as sudden and brittle and thus should not be the dominant failure mechanism for structural members. It is anticipated that SHCC laminates can increase the shear capacity of a hybrid structure compared to a conventional RC structure. However, the fracture behaviour under shear load in hybrid systems is not yet fully understood, as fracture properties are influenced by factors such as concrete strength, curing age, volume fraction of fibres, aggregates, and the interface between conventional concrete and SHCC. Depending on the surface pre-treatment during manufacturing, a premature debonding of SHCC laminates from a traditional concrete core can happen, which can outweigh the benefits of SHCC application.

2 Composition and general properties of strain-hardening cementitious composite (SHCC)

SHCC is a cement-based material originally developed by Victor Li in the 1990s [10], under the name Engineered Cementitious Composite (ECC). A special micromechanics design of matrix, containing fibres and only fine particles provides a "microcrack bridging property" and improved crack control ability with multiple microcracks rather than a single concentrated crack. As a result, pseudo strain-hardening behaviour under tension, as illustrated in Figure 1, is obtained. This characteristic has led researchers to name it "Strain Hardening”. SHCC shows high deformability up to a tensile strain of around 5%. In comparison, the maximum tensile strain of traditional concrete is approximately 0.01%. Due to its decreased brittleness, SHCC is reported to be a promising repair material [4] and has increased bond strength and abrasion resistance [11].

Over the years, different mixtures of SHCC were developed, starting with a traditional one that includes Ordinary Portland Cement (OPC), fly ash, and silica sand with a relatively low fibre content of 2% or less by volume. The substitution of fly ash with blast furnace slag and silicate sand with limestone powder were applied shortly after. Variations in mixture composition considered both the inclusion of coarse sand and fine nanomaterial additives as well. In order to reduce curing time when SHCC is applied for repair, different chemical admixtures that accelerate hydration and hardening were added to SHCC. Mixtures with improved viscosity and bond strength aim to enable better workability and prevent early failure of the repair. More improvements addressing certain properties included: enhancing micro-cracking capacity and ductility by adding polystyrene beads to the mix, including recycled tyre rubber to decrease the modulus of elasticity of the material, including pre-soaked expanded perlite aggregate to reduce shrinkage, or adding super absorbent polymer (SAP) or bacteria to enhance the self-healing of microcracks. Most of these attempts aim at one of two goals: increasing the bond strength between the two materials or/and improving a certain property of the (repair) material (i.e., reducing shrinkage, reducing eigenstresses, increasing strength, triggering self-healing properties, etc.).

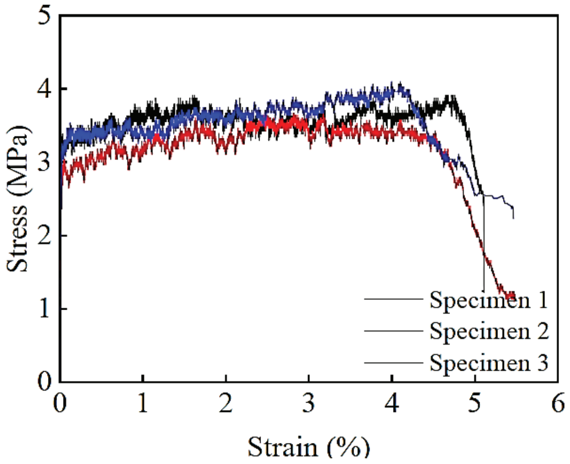

Figure 1. Example of tensile stress–strain curves of SHCC at the age of 28 days [12]

The characteristic behaviour of SHCC includes small crack widths ranging from 60 µm to 100 µm [4] and significant ductility after cracking, with a strain capacity two orders of magnitude higher than that of traditional concrete [13]. Small crack widths in SHCC offer two key advantages. Firstly, it exhibits good self-healing properties [14]. Secondly, water permeability through those cracks is similar to that of uncracked concrete [15]. As a result, it is anticipated that the service life of a SHCC will be longer than that of a NC. However, if SHCC is to be used as a complete replacement for traditional reinforced concrete, it is neither environmentally nor financially feasible for the construction industry due to the higher amount of binder and higher cost of ingredients used in SHCC. The use of Polyvinyl Alcohol (PVA), as well as other types of fibres, often increases the overall cost of SHCC; therefore, their use must be justified.

2.1 Fibres

There are many types of fibres used in SHCC. According to [13], different fibres have an influence on crack width control in hybrid structures containing SHCC and traditional concrete. The most common fibres from the literature review are Polyvinyl Alcohol (PVA) fibres, High Modulus Polyethylene (HMPE) fibres, and steel fibres (Figure 2). Attempts are also made to use natural fibres in SHCC [16].

After the formation of a crack, fibres play a crucial role in the micromechanical design by increasing the post-cracking strength. There is a common misconception that fibres prevent the formation of cracks, but in reality, the crack appears at the same load level as in traditional concrete. However, the fibres control the crack width. The small crack width in SHCC results in a longer service life of the structure since narrow cracks can slow down the ingress of chloride ions and thus better prevent reinforcement from corroding. Namely, due to the high ductility of SHCC, corrosion-induced expansion leads to controlled splitting cracks, and the probability of spalling is reduced. Cracks are very small and are filled with corrosion products, which is not the case with reference concrete [20]. Further ingress of deleterious materials is also prevented, and this finally leads to a reduced corrosion rate, as observed by Jen and Ostertag [21] and Miyazato and Hiraishi [22].

Figure 2. Photo on the left: Polyvinyl Alcohol (PVA) fibres [17]. Photo in the centre: High Modulus Polyethylene (HMPE) fibres [18]. Photo on the right: steel fibres [19]

The precise effect of fibres on the behaviour of concrete or SHCC is dependent on the type and volume fraction of the fibres used.The hydrophilic surface of PVA fibres is attributed to the presence of a hydroxyl group in their structure. They can retain their strength even at an elevated temperature of 150°C [23]. PVA fibres are well known for forming strong chemical bonds with the matrix, which require a considerable amount of energy to break [13]. However, the ductility of SHCC may be negatively impacted because the fibres may rupture before the bond slips. They have a reputation for high resistance to alkali, UV, chemicals, and abrasion, as reported by the manufacturer [16]. PVA fibres are also stable under heat and moisture exposure [24] and are not susceptible to corrosion. Nonetheless, their higher cost compared to other alternatives is a disadvantage.

The high modulus polyethylene (HMPE) fibres are long chains of aliphatic hydrocarbon [25], making it a thermoplastic substance with a glass transition temperature of approximately -120°C. These polymer chains are not vulnerable to chemical attack due to the absence of chemical groups that can attract acids, alkalis, or other chemicals at room temperature that could break the chains [26]. Consequently, HMPE fibres possess excellent chemical resistance. However, their hydrophobic nature causes them to form weak adhesion bonds with the cementitious matrix [13]. Despite their high tensile strength and modulus of elasticity, their low density keeps them relatively lightweight. Compared to PVA fibres, they are approximately twice as strong [13], but the ultimate strain at which they break is relatively low. Nevertheless, the weak matrix-fibre interface in combination with higher tensile strength leads to greater ductility in SHCC compared to SHCC with PVA fibres [27].

Steel fibres are commonly used due to their relatively low production costs. They marginally improve compressive strength, but can enhance tensile strength up to 40%, according to [28]. The use of steel fibres also results in significant improvements in post-peak ultimate strain and ductility. The bonding strength between steel fibres and the matrix can easily be adjusted compared to other types of fibres. Steel fibres with hooks can be manufactured to create mechanical interlocking with the matrix in addition to friction and adhesion at the interface [29]. However, steel fibres have disadvantages such as high self-weight and poor workability [28]. Steel fibres embedded in concrete are prone to corrosion when exposed to low-pH environments or chemicals [30]. Nevertheless, if concrete is well-compacted and sufficient cover is applied, this is not a threat to members' integrity and performance. The damage will be limited to the exposed surfaces.

3 Characteristic properties of SHCC

3.1 Shrinkage

PVA fibres and the fibre-matrix interface do not contribute significantly to the driving mechanism of, e.g., drying shrinkage, which is caused by moisture migration to a lower relative humidity environment. However, there are fibres that do absorb a significant amount of moisture, e.g., natural fibres. According to [31], natural fibres will swell or shrink depending on relative humidity. This change in strain has an influence on the bond between fibre and matrix.

The amount of drying shrinkage in SHCC is significantly higher when compared to that of NC [32]. The typical drying shrinkage of NC is in the range between 50 μm/m and 350 μm/m[33]. The ultimate drying shrinkage strain of SHCC may be between 1200 μm/m and 2500 μm/m [34, 35]. This means that the drying shrinkage of SHCC is at least twice as large compared to NC. The primary cause of such large drying shrinkage in SHCC is a relatively larger binder content in typical SHCC compared to normal (traditional) concrete. Since the shrinkage of aggregates is significantly lower than that of the hydrating paste, a material with a higher cement content will shrink more. The secondary cause is the small aggregate size that is used in SHCC. In general, large aggregates restrain shrinkage and reduce total shrinkage strain [36]. Still, as long as the strain capacity of SHCC is significantly larger than its shrinkage strain, it is expected that no localized cracks in SHCC will appear. Instead, it will have rather many fine shrinkage cracks [4].

3.2 Environmental burden of strain hardening cementitious composite

On the edge of climate change, no place on the globe would be free from the consequences of rising temperatures. The number of wildfires increases; sea levels are rising; contamination of drinking water is increasing; and the rate of decrease in biodiversity has never been faster due to human activity. Those events may seem overwhelming at first, but there are things that our civilization can do to prevent them from happening. From the construction point of view, if a structure has a longer service life, i.e., is more durable but at the same time more sustainable, this could be one of the main pillars of preventing global climate change from happening. In contrast to the past, the modern civil engineer is more aware of problems that the traditional linear building process may lead to.

Among all construction materials, concrete is currently the most widely used material on the planet. Unfortunately, concrete requires huge volumes of primary resources, which causes the depletion of natural resources. The production of cement is a highly energy-intensive process because the cement kiln has to operate at a high temperature of approximately 1450 to 1600°C. To sustain this heat energy, a large volume of fossil fuel is burned, leading to the release of pollution into the air, water, and soil. The largest problem is the emission of huge quantities of carbon dioxide (CO_2) into the atmosphere due to the burning of fossil fuels. CO_2 is released during the decomposition of calcium carbonate ($CaCO_3$) into calcium oxide (CaO) and CO_2. The environmental impact of the production of concrete may seem bad, but well-designed concrete members can last for many decades, even in a harsh environment. So, the environmental burden can be spread over many years of its service life. As a result, concrete may be a sustainable alternative if it is applied wisely.

The environmental impact of SHCC is higher than traditional concrete for three reasons. Firstly, SHCC makes use of fibres that have to be produced and transported, and are more difficult to recycle afterwards from the mix. This component material is not used in NC. Secondly, the lack of coarse aggregates in SHCC leads to a higher consumption of binder compared to NC. Thirdly, it is the larger portion of chemical admixtures and a super-plasticizer that have to be added, which also contribute significantly to the environmental impact of SHCC. To systematically analyse the environmental burden of both materials, Li [7] has conducted a Life Cycle Analysis (LCA) of SHCC and NC. The main results from this paper are shown in Figure 3. The functional unit in this paper was defined as ‘1000 kg of material’. It is a subject for debate if this is an appropriate functional unit. Due to the superior properties of SHCC compared to conventional concrete, less SHCC might be needed for the same performance criteria. For example, the application of SHCC link slabs is common in Japan. In a case study, for a life cycle of 60 years, a traditional bridge with conventional steel expansion joints was compared to a traditional bridge with SHCC link slab [37]. On a material basis, the production of SHCC consumes 1.8 times the energy consumed for the production of conventional steel-reinforced concrete (1% steel by volume). A similar trend is obtained if other sustainability indicators are compared. However, SHCC properties are expected to extend the service life of the SHCC system to twice that of the conventional system, resulting in significantly lower total life cycle energy consumption. Finally, the results indicate that the SHCC bridge deck system has 40% less life cycle energy consumption, 50% less solid waste generation, and 38% less raw material consumption. Construction-related traffic congestion and maintenance are the greatest contributors in most life cycle impact categories. However, it has to be highlighted that this analysis was based on the assumption that the SHCC link slab would double the life expectancy of the bridge deck relative to the conventional steel joint.

There are ways to improve the sustainability of SHCC. The development of green SHCCs, with examples in the adoption of alternative binder/filler, sand, and fibre, is analysed in [7]. Alternative ingredients may have a lower energy/carbon intensity, be sourced from industrial waste streams, or be renewable. According to [25], HMPE fibres have a lower carbon footprint compared to steel fibres or any other synthetic fibre (e.g., PVA fibres) due to the higher strength/weight ratio of HMPE fibres. However, SHCC sustainability derives mainly from its durability under a variety of exposure conditions, in particular the intrinsically tight crack width (below 100 μm) which minimizes the impacts of crack-related deterioration mechanisms. Apart from the tight crack width that slows the ingress of aggressive agents through the concrete cover, the ductility of SHCC provides an additional means of service life extension through the suppression of cover spalling tendency once reinforcement corrosion is initiated [7]. Therefore, care should be taken when introducing certain types of industrial waste or recycled sand into SHCC, as they could eventually affect the mechanical performance of SHCC and thereby its long-term benefits.

Finally, due to its relatively high environmental impact per unit volume, SHCC should not be used in places where its excellent durability aspects cannot be utilized. Instead, SHCC should be used as a durability enhancement for reinforced concrete at the most susceptible locations in the structure (e.g., cover, heavily loaded tension zones).

3.3 Bonding properties of Strain Hardening Cementitious Composite to concrete

When used for the repair of old/deteriorated concrete structures, traditional concrete or mortar is brittle and can exhibit large cracks or debonding of the interface. To improve the service performance of concrete structures and address the inherent brittleness of repair materials, SHCC was introduced as a promising repair material. For this reason, so far, research has focused mostly on the bonding properties between the freshly cast SHCC and the existing, old NC. The effect of the interface between freshly cast NC and an older SHCC, which might be a governing situation for innovative hybrid SHCC structures when SHCC is used as a stay-in-place mould for concrete, is rarely studied.

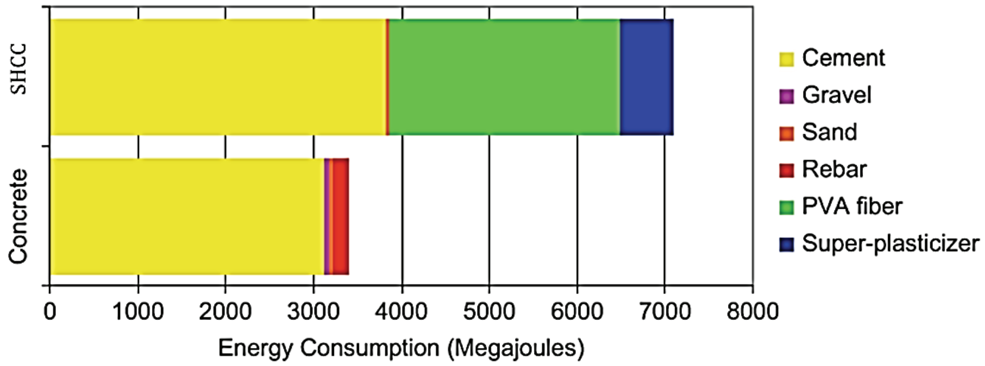

Figure 3. Energy consumption per 1000 kg of steel reinforced concrete and SHCC [7]

The bond strength of the SHCC-to-concrete interface under shear load depends on the compressive strengths of SHCC and NC, the curing age of the specimen, the curing environment (temperature and relative humidity), the interface roughness, the type of fibres used, and, if applied, additional binding agent strength. Those influencing factors were experimentally investigated by Tian et al. [38] and Gao et al. [39].

The research conducted by Tian et al. [38] has found that the roughness of the interface is the most dominant factor in the failure mode (as the higher roughness of a surface provides a larger contact area), while SHCC strength class and fibre types play a secondary role. The higher roughness of a surface provides a higher contact area. To determine the roughness of the surface, the surface profile of exposed aggregates on the interface was measured, and then the average height (the interface roughness value) was evaluated. According to [40], the limit value for the interface roughness value is about 4-5 mm. Values higher than this result in a weaker interface. In those experiments, the bond strength between cast-in-situ Ultra-High Toughness Cementitious Composite (UHTCC) and old concrete specimens was tested in a pull-out setup. UHTCC is similar to SHCC but has much higher strength. Furthermore, in [36], it was found that higher SHCC compressive strength led to higher interface shear strength and that PVA fibres with higher ultimate tensile strength only marginally influenced the shear strength [38].

Two types of specimens were widely used to investigate the shear bonding strength of the interface (Figure 4). Three slant shear specimens consisting of SHCC with a 28-day compressive strength of 39,9 (±0,38) MPa and NC C35/45 have been tested in the research presented by Gao et al. [39]. The mean shear strength value that has been found at room temperature is 5,5 MPa. However, two of the three specimens were broken before loading, so there is no data about the standard deviation or the variation coefficient. Furthermore, the heat treatment up to 200°C after standard curing for 28 days had a beneficial effect on the strength. The shear strength value at 200°C equals 6,87 (±0,87) MPa with a variation coefficient of 12,7%. The shear strength values after exposure to temperatures beyond 200°C were worse than at room temperature.

The researchers, Tian et al. [38] used single-sided shear specimens to obtain shear strength. In this research, one type of NC C40/50 and four different types of SHCC with different 28-day compressive strengths (from 21.7 MPa up to 40.8 MPa) have been used. The interface shear strength was found in a range between 0,33 (±0,04) MPa for low-strength class ECC and 1,11 (±0,15) MPa for high-strength class SHCC. The specimens with a thick epoxy resin layer with coarse aggregates applied on the interface resulted in the following shear strength range: 0,86 (±0.08) MPa for low-strength SHCC and 3,33 (±0,13) MPa for high-strength SHCC.

To enhance the bonding strength of the interface, additives could be added at the cement manufacturing stage. According to relevant literature [40, 41], fly ash, slag, and silica fume can improve the bond properties of the interface. In addition, there are different admixtures that could improve bonding property, e.g. expansive agent and SBR latex [40]. According to the slant shear test conducted by [41], 52,8% higher bonding strength was obtained by SHCC with slag at the age of 28 days compared to the monolithic concrete reference specimens. SHCC with fly ash improved the bonding strength by 36,4% compared to the reference specimens. The reference specimens were made of concrete with a 28-day compressive strength of 31,9 (±1,1) MPa.

The results presented in [24, 41, 42] show that concrete with PVA fibres had significantly better bonding performance than NC, so in general, the SHCC-to-concrete interface was stronger than a concrete-to-concrete interface.

The main conclusion drawn from these experiments is that SHCC can achieve a strong bond with concrete. Moreover, this should be possible without any prior preparation of the surface. This is a rather promising clue for further research, and even more so for practical applications where practices such as preparation are most likely very costly and environmentally expensive. Although a thick epoxy resin layer with coarse aggregates gives the highest interface shear strength, it is unlikely to be used in practice due to its high cost. Nevertheless, it can increase strength by a factor of 3, as demonstrated in [38].

3.4 Shrinkage induced debonding

The differential (drying and/or thermal) shrinkage between SHCC laminate and NC may cause a bonding failure at the interface. Restrained drying, shrinkage degradation, and resulting interface stresses are the major contributors to this failure [4]. Due to restrained shrinkage deformations, the generated stress causes delamination between SHCC and NC. Therefore, the properties of SHCC should be chosen not only based on strength performance but also on the exposure environment and ductility of the interface.

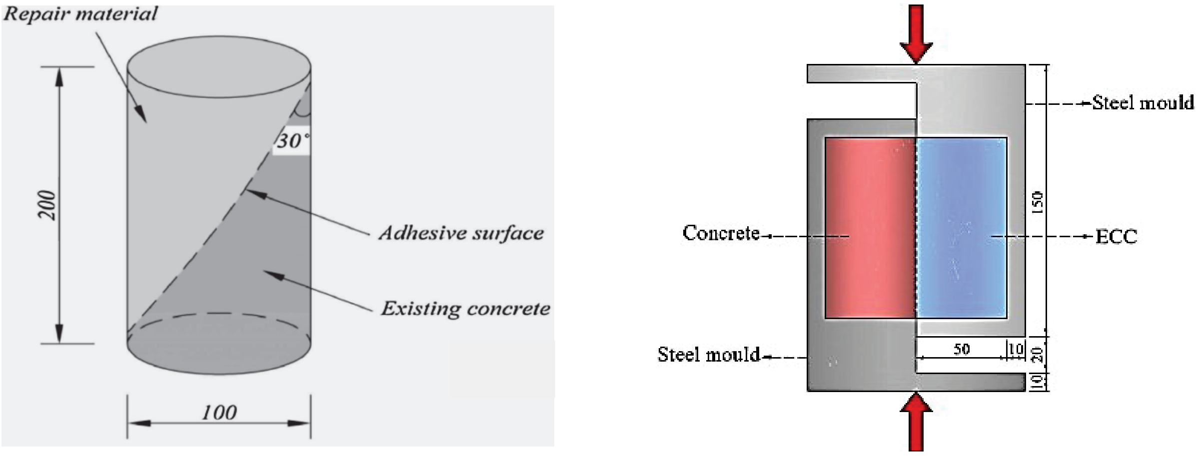

Figure 4. Left: The slant shear specimen according to American ASTM C882 standard [39]. Right: Single-sided shear test setup [38]

Next to material properties, an interlocking mechanism plays a significant role in counteracting the shrinkage at the interface between SHCC and NC. Despite reviewing the database of scientific papers and books, no systematic experiment has been found that evaluated the effectiveness of SHCC surface roughness on damage caused by shrinkage and its residual interface strength .

4 Experimental benchmarks on RC beams with shear strengthening using SHCC

The major advantages and disadvantages of SHCC have been described above. In theory, an optimal solution would be to apply SHCC and NC together in a so-called hybrid system. In this way, those materials should cover their mutual shortcomings. This chapter will give an overview of the experiments in which hybrid SHCC-concrete beams were tested under shear loads.

Before 2015, there was hardly any knowledge about the shear behaviour of hybrid SHCC-concrete beams. The first research on the shear behaviour of RC beams without transverse reinforcement strengthened by SHCC layers was conducted by Zhang et al. [43]. In 2019, Wang et al. [44] conducted a similar experiment but on slightly larger members and thicker SHCC layers. A year later, Wei et al. [45] published their work on the shear behaviour of hybrid RC beams with transverse reinforcement. The experiment was successful, but their hybrid beams experienced minor delamination of SHCC laminates just before the peak load.

There are also some other types of hybrid beams strengthened by SHCC and tested for shear capacity. In 2018, Wu et al. [46] tested RC beams strengthened by precast thin-walled (20-mm) U-shape UHTCC. Multiple M16 penetrating bolts have been added to improve the integration of the U-shape. The increase in shear strength reached 67,4% [46]. In 2020, Shang et al. [47] proved that U-shape SHCC with stirrups is an effective way of shear-strengthening damaged RC beams due to fire. Recent research (2022) by Li et al. [48] showed the great potential of thin-walled (15-mm and 25-mm) U-shapes in their experiments to enhance the shear strength of RC beams with and without transverse reinforcement. The relative increase in shear resistance ranged between 8,40% and 66,39% [48]. Two relevant studies, considering SHCC strengthening of a beam with and without shear reinforcement, are further presented in detail.

Experimental investigation by Zhang et al. [43] on shear capacity of RC beams without transverse reinforcement strengthened by SHCC laminates

The paper presents an experimental investigation of the SHCC laminate-strengthened RC beams without transverse reinforcement. This research focuses on the shear load carrying capacity of such a hybrid beam. Additionally, they documented the crack pattern of their hybrid beams.

In Table 1, the list of ingredients was provided for SHCC, with a 28-day compressive strength of 91 MPa used during the experiment [43]. As it can be deducted, the water-cement ratio equals 0,27, and the water-to-binder (cement + silica fume) ratio equals 0,22. The results obtained from the uniaxial tensile test on the dog bone specimens are shown in Figure 5. All specimens exhibited significant strain hardening behavior until ultimate tensile strength (point B1 or B2). Multiple fine cracks occurred and propagated after reaching the initial cracking (point A) until reaching the peak strength. Thereafter, tensile stress decreased due to the localization of some cracks. Young's modulus of SHCC is estimated to be around 29 GPa.

Table 1. Mix proportions of SHCC[43]

Component	Dry Weight [kg/m^3]
Cement {not specified}	1267,9
Silica fume	230,8
Fine sand	153,9
Expansion agent	40,0
Water	338,5
Superplasticizer	15,4
PE fibres	14,6
Air reducing agent	0,06

The list of ingredients in NC was not provided in this paper. The only information known about this concrete is that it had a 28-day compressive strength of 27 MPa and a Young's modulus of 23,5 GPa.

In Figure 6, the schematization of the hybrid beam is shown. The specimens were reinforced with two steel longitudinal ribbed bars with a diameter of 10 mm. No shear reinforcement has been applied. The steel, which was used for this reinforcement, has a yield strength of 345 MPa and a Young's modulus of 200 GPa [43]. The beam span was chosen to be 1 m, which results in 0.5 m of shear span, and

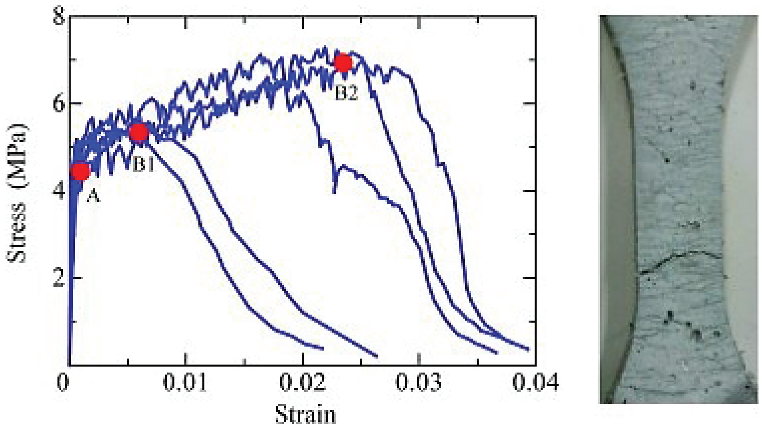

Figure 5. Uniaxial tensile test results of SHCC [43]

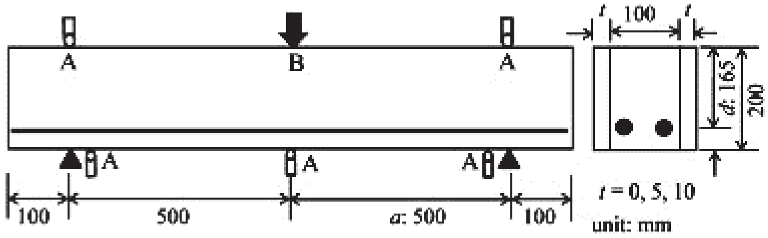

Figure 6. Geometry of RC beams strengthened by SHCC laminates [43]

this corresponds to $\eta_a \approx 3{,}0$. The beam, having a cross-section of 100 x 200 mm^2 was strengthened by casting SHCC laminates with a thickness of 5 mm or 10 mm on two sides. Before SHCC was cast on the side surface, those sides 'were washed out using a retarder to obtain roughed surfaces' quoting from [43].

Figure 7 shows the results of the experiment. The beam strengthened by 10 mm SHCC laminates has reached the highest shear load capacity of about 90 kN. That is almost twice the capacity of the reference beam. The beam strengthened by 5 mm SHCC laminates has reached about 70 kN. Even though Young's modulus of this SHCC is higher than that of normal concrete, the beams followed the same linear elastic branch up to a certain point.

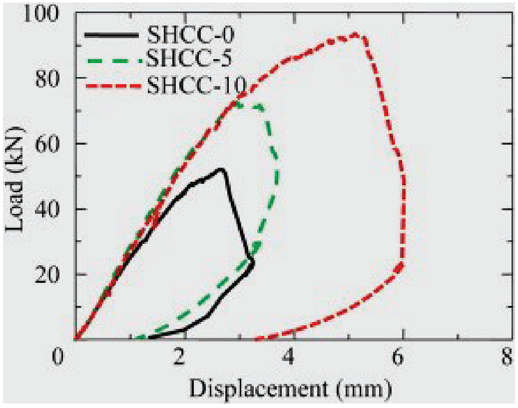

Figure 7. Load–displacement curve. SHCC-0 is the RC beam without SHCC laminates. SHCC-5 is the RC beam with 5 mm thick SHCC laminates. SHCC-10 is the RC beam with 10 mm thick SHCC laminates [43]

A comparison between the ultimate crack distribution of the shear-failed SHCC member and structural elements strengthened with the SHCC layer is demonstrated in Figure 8. For the SHCC member, it was observed that there were many multiple fine cracks in the diagonal shear direction of the SHCC member due to the fibre bridging effect. The beam finally failed in shear due to the localization of a critical crack. Finally, there was only one localized diagonal shear crack with a few accompanied small cracks in the vicinity, indicating that the ductility of SHCC has not been fully exploited when used for shear strengthening of RC members. This is in line with earlier observations when SHCC is used for repair.

Experimental investigation by Wei et al. [45] on shear capacity of RC beams with transverse reinforcement strengthened by high-strength SHCC laminates

This experimental study has a more realistic scenario than the previous one due to the use of transverse reinforcement. This research tries to answer the following question: whether SHCC laminates are efficient in the shear strengthening of reinforced concrete structures?

Table 2 Mix proportions of HS-SHCC[45]

Component	**Massa ratio**
Cement {not specified}	0,8
Silica fume	0,2
Sand	0,3
Water	0,2

+ 2% PE fibres by volume of the mixture

2 provides the mix design list for the HS-SHCC used. To maintain workability, a polycarboxylate-based superplasticizer was added to the mix. Polyethylene (PE) fiber (12mm long and 24μm in diameter) was chosen due to its excellent tensile strength and high modulus. Very fine sand with particle sizes of 0.125mm - 0.18mm was used.

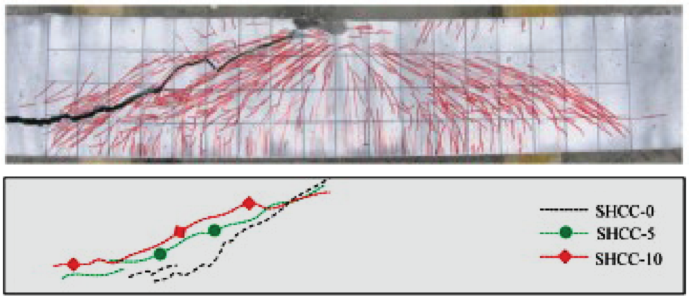

Figure 8. Positions of localized cracks. SHCC-0 is the RC beam without SHCC laminates. SHCC-5 and SHCC-10 are the RC beams with 5 mm and 10 mm thick SHCC laminates, respectively [43]

According to tests on small cubes (40x40x40 mm^3) by Wei et al. [45], a 28-day compressive strength of 120 MPa has been reached. Furthermore, the tensile strength of 10 MPa on dog bone specimens has been reported, as seen in Figure 9, and Young's modulus of 35 GPa.

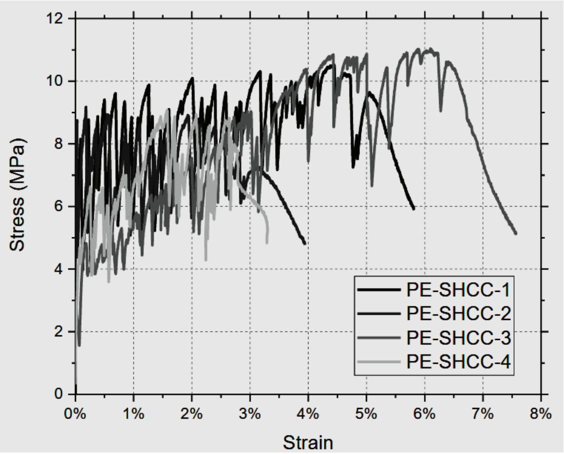

Figure 9. Tensile stress-strain curves of HS-SHCC 28 day direct tension test [45]

The properties of the NC were as follows: 36 MPa for 28-day compressive strength, and 26 GPa for Young's modulus. The compressive strength was tested on 100 x 100 x 100 mm^3 cubes.

This research paper [5] documents experimental beams with two different shear span parameters: 'Group A' with $\eta_a = 1{,}5$ and 'Group B' with $\eta_a = 2{,}5$. In group B, four beams have been tested: two reference beams and two hybrid beams. The detailed geometry of the beams is shown in Figure 10. The hybrid beams were only strengthened on one side (in the red area). The reinforcement steel has a yield strength of 585 MPa and a Young's modulus of 200 GPa. The SHCC laminates had a thickness of 10 mm and were cured for 28 days. Those laminates were cast directly on the surfaces of the beams. The loading speed for all beams was set to 0,01 mm/s.

All beams have failed in shear and developed large diagonal cracks. Furthermore, minor debonding of SHCC laminates was initiated, but they did not completely delaminate from the beams. In Figure 11, the results of the experiment are shown.

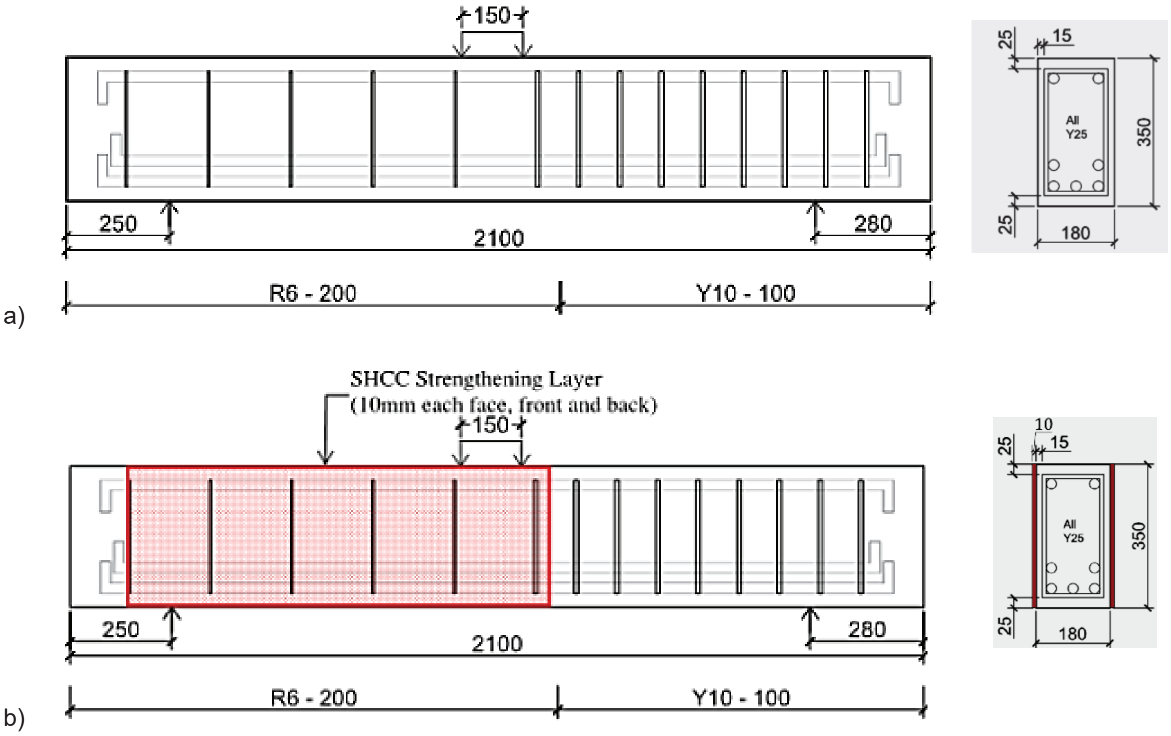

Figure 10. Group B: a) Geometry of reference RC beams. b) Geometry of hybrid beams strengthen by HS-SHCC laminates (red area) [45]

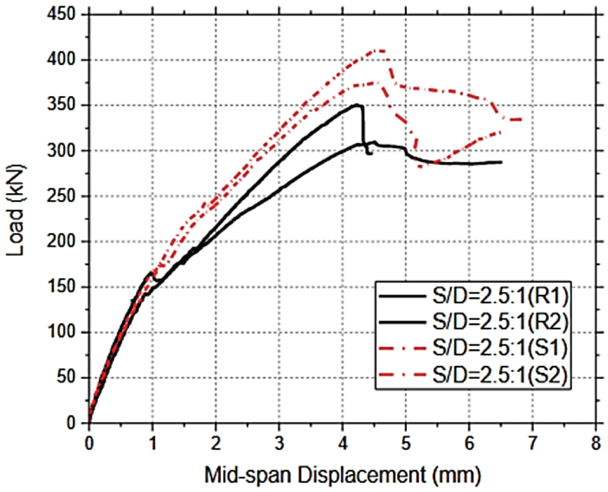

Figure 11. Load–displacement curve. R1 and R2 are the refence beams.
S1 and S2 are hybrid beams [45]

The shear capacity of the hybrid beam has increased by 19% compared to the reference beams [45]. The strength of the interface between NC and HS-SHCC was what determined the strength of the hybrid beams. This could mean that the utilization of HS-SHCC laminates was not complete, and thus the hybrid beams could have reached a higher shear capacity than the results presented in Figure 11. The shear failures of the hybrid beams were still of a brittle nature, like the shear failures of the reference beams.

5 Conclusions

Based on the above presented literature review, the following conclusions can be drawn:

- SHCC has superior tensile properties compared to concrete. Those properties are highly dependent on the composition of the mix:
  - The main benefit of SHCC is its high ductility. The range of tensile strain at 90% strength is somewhere between 2% and 5% [18, 43].
  - A typical crack pattern in SHCC consists of multiple parallel cracks. This is more advantageous than one concentrated crack like in NC because the width of an individual SHCC crack is significantly smaller. The width of cracks in SHCC ranges between 60 μm and 100 μm. The advantages of a smaller crack width are:
    - Good self-healing properties,
    - Smaller water permeability and ingress of hazardous substances: water with ions is one of the ingredients that lead to the corrosion of reinforcement.
  - The common range of the tensile strength of an SHCC is between 2 and 8 MPa. Yet, it highly depends on many factors like type of binder, w/c ratio, fibre volume fraction, and type of fibres. High-strength strain-hardening cementitious composites (HS-SHCC) with over 10 MPa tensile strength [43] have also been developed.
- SHCC has great durability but does not belong to the low environmental burden materials, according to Li [7]. SHCC can be more sustainable than NC only if its superior properties are utilized. In other cases, there is more damage done to the natural environment than is worth it.
- There is still a lack of knowledge regarding the concrete connection between old SHCC and young NC. Most of the current experiments [43, 44, 46] on this subject have been performed on the interface between young SHCC and old normal concrete. Based on experiments [38] conducted by Tian et al., the positive effect on the interfacial shear strength is mainly due to higher SHCC compressive strength and interfacial roughness. The secondary parameter, which is positively correlated with the interfacial shear strength, is the ultimate tensile strength of fibres, according to data presented in [38]. Based on experiments [39] conducted by Gao et al., the limited temperature treatment (< 200°C) might be beneficial to the bonding performance of the interface, but at extreme values (> 200°C), the interfacial shear strength is lower. Furthermore, Şahmaran et al. [41] have discovered that SHCC with slag has a higher bond shear strength than SHCC with fly ash. However, the contribution of slag in SHCC should be denoted as the secondary parameter since the primary parameters (SHCC compressive strength and interfacial roughness) had much greater effects on the interfacial shear strength.

- The most effective way to increase interfacial strength between SHCC and NC is to add roughness to the surface and increase the strength of SHCC. This can be used as guidance when designing the hybrid interface. So far, no efforts have been made to increase the ductility of the interface.

- The biggest disadvantage of SHCC is its significant magnitude and rate of drying shrinkage compared to that of NC. In most cases, the drying shrinkage of SHCC is at least twice as high as that of NC. This has a huge negative consequence for interfaces between SHCC and NC because they are prone to delamination.

- Recently, scientists conducted a few experimental investigations [43-48] on the shear behaviour of RC beams, with and without transverse reinforcement, strengthened with SHCC laminate. Using SHCC laminates with a thickness of 10 mm improves shear capacity by 18% to 50%. This ratio is dependent on the tensile and elastic properties of SHCC compared to those of the base concrete. The shear failures of those hybrid beams were still as brittle and sudden as those in control groups. Some of the tested hybrid beams showed debonding of SHCC laminates, which resulted in premature failure.

Acknowledgement

The authors would like to acknowledge the financial support of the Science Fund of the Republic of Serbia through the Serbian Science and Diaspora Collaboration Program and project: "Hybrid Solution for Improved Green Concrete Performance – HyCRETE".

Mladena Luković would also like to acknowledge the Dutch Organization for Scientific Research (NWO) for the grant "Optimization of interface behavior for innovative hybrid concrete structures" (project number 16814)."

References

[1] C.R. Gagg, Cement and concrete as an engineering material: An historic appraisal and case study analysis, Engineering Failure Analysis, 40 (2014) 114-140. https://doi.org/10.1016/j.engfailanal.2014.02.004

[2] A. T. Marsh, A. P. Velenturf,S. A Bernal, Circular Economy strategies for concrete: implementation and integration, Journal of Cleaner Production, 362 (2022) 132486. https://doi.org/10.1016/j.jclepro.2022.132486

[3] Y. Liu, B. Pang,Y. Wang, C. Shi, B. Zhang, X. Guo, S. Zhou, J. Wang, Life-cycle maintenance strategy of bridges considering reliability, environment, cost and failure probability CO2 emission reduction: A bridge study with climate scenarios. Journal of Cleaner Production, 379 (2022) 134740. https://doi.org/10.1016/j.jclepro.2022.134740

[4] M. Luković, Influence of interface and Strain Hardening Cementitious Composite (SHCC) properties on the performance of concrete repairs, PhD thesis, TU Delft, 2016, ISBN 978-94-6186-590-8

[5] M. Luković, D.A. Hordijk, Z. Huang, E. Schlangen, Strain hardening cementitious composite (SHCC) for crack width control in reinforced concrete beams, Heron, 64 (1/2) (2019) 189-206

[6] E. Schlangen, B. Šavija, S.C. Figueiredo, F.F. de Mendoça Filho, M. Luković, Mechanical Properties of Ductile Cementitious Composites Incorporating Microencapsulated Phase Change Materials, Strain-Hardening Cement-Based Composites (2017) 115–122. https://doi.org/10.1007/978-94-024-1194-2_13

[7] V.C. Li, Sustainability of Engineered Cementitious Composites (ECC) Infrastructure. In: Engineered Cementitious Composites (ECC), 2019, Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-58438-5_8

[8] S. Mustafa, S. Singh, D. Hordijk, E. Schlangen, M. Luković, Experimental and numerical investigation on the role of interface for crack-width control of hybrid SHCC concrete beams, Engineering Structures, 251 (2022) 113378. https://doi.org/10.1016/j.engstruct.2021.113378

[9] A. Arif, Numerical Study of Shear Strengthening of Reinforced Concrete Beams using Strain-Hardening Cementitious Composites, MSc thesis, TU Delft, 2020

[10] V.C. Li, On engineered cementitious composites (ECC) a review of the material and its applications, Journal of advanced concrete technology, 1(3) (2003) 215-230.

[11] J. Zhao, T. Song,Fibre-Reinforced Rapid Repair Material for Concrete Pavement, Advanced Materials Research 168 (2011) 870. https://doi.org/10.4028/www.scientific.net/AMR.168-170.870

[12] P. Wang, M. Jiao, C. Hu, L. Tian, T. Zhao, D. Lei, F. Hua, Research on Bonding and Shrinkage Properties of SHCC-Repaired Concrete Beams, Materials 13(7) (2020)1757 https://doi.org/10.3390/ma13071757

[13] S. Mustafa, S. Singh, D. Hordijk, E. Schlangen, M. Luković, Experimental and numerical investigation on the role of interface for crack-width control of hybrid SHCC concrete beams, Engineering Structures, 251 Part 1 (2022) 113378 https://doi.org/10.1016/j.engstruct.2021.113378

[14] S. Qian, J. Zhou, M.R. De Rooij, E. Schlangen, G. Ye, K. Van Breugel, Self-healing behavior of strain hardening cementitious composites incorporating local waste materials, Cement and Concrete Composites 31 (2009) 613-621 https://doi.org/10.1016/j.cemconcomp.2009.03.003

[15] M.D. Lepech, V.C Li, Water permeability of engineered cementitious composites, Cement and Concrete Composites 31 (2009) 744-753 https://doi.org/10.1016/j.cemconcomp.2009.07.002

[16] M.G. Sierra-Beltran, Ductile Cement-Based Composites with Wood Fibres-material design and experimental approach, PhD thesis, TU Delft (2011).

[17] The Yarn Guru India Inc, PVA Fibre for Concrete, For Construction. https://www.indiamart.com/proddetail/pva-fibre-for-concrete-19546384673.html (accessed 10 January 2022)

[18] S. Ahammed,High Modulus Polyethylene (HMPE) https://www.slideshare.net/SAMIUN0501/high-modulus-polyethylene-hmpe (accessed 10 January 2022)

[19] W. Lin, T. Yoda, Chapter Seven - Steel Bridges, in:W. Lin, T. Yoda (Eds.) Bridge Engineering, Butterworth-Heinemann, 2017, pp. 111-136. https://doi.org/10.1016/B978-0-12-804432-2.00007-4

[20] B. Šavija, M. Luković, S.A.S. Hosseini, J. Pacheco and E. Schlangen (2015). Corrosion induced cover cracking studied by X-ray computed tomography, nanoindentation, and energy dispersive X-ray spectrometry (EDS). Materials and Structures, 48, pp.2043-2062. https://doi.org/10.1617/s11527-014-0292-9

[21] Jen G, Ostertag CP. Experimental observations of self-consolidated hybrid fiber reinforced concrete (SC-HyFRC) on corrosion damage reduction. Construction and Building Materials. 2016 Feb 15;105:262-8.https://doi.org/10.1016/j.conbuildmat.2015.12.076

[22] S. Miyazato & Y. Hiraishi (2013). Durability against steel corrosion of HPFRCC with bending cracks. Journal of Advanced Concrete Technology, 11, 135-143.https://doi.org/10.3151/jact.11.135

[23] J. M. Illston, P. Domone, Construction Materials — Their nature and behaviour, in: M. Soutsos, P. Domone (Eds.) Third Edition, 2001, ISBN 0-419-26860

[24] E. Du,S. Dong, J. Sun, Concrete Bonding Properties of Polyvinyl-Alcohol Fibre in Fabricated Structures, Chemical Engineering Transactions, 66 (2018) 1057-1062. https://doi.org/10.3303/CET1866177

[25] M.I. Kiron, High Performance Polyethylene Fibres – An Overview. https://textilelearner.net/high-performance-polyethylene-fibres-an-overview/ (accessed 3 January 2022)

[26] M. Vlasblom, The manufacture, properties, and applications of high-strength, high-modulus polyethylene fibres, Handbook of Properties of Textile and Technical Fibres (Second Edition), 2018, 66, 699-755. https://doi.org/10.1016/B978-0-08-101272-7.00018-3

[27] V.C Li, Engineered Cementitious Composites (ECC), Bendable Concrete for Sustainable and Resilient Infrastructure, Springer Berlin Heidelberg, 2019

[28] P. R. Tadepalli, Y.L. Mo, T.T.C Hsu, Mechanical properties of steel fibre concrete, Magazine of Concrete Research 65(8) (2015) 462-474. https://doi.org/10.1680/macr.12.00077

[29] S. Abdallah, M. Fan, D.W.A. Rees, Bonding Mechanisms and Strength of Steel Fibre–Reinforced Cementitious Composites: Overview, Journal of Materials in Civil Engineering 30 (2018) https://doi.org/10.1061/(ASCE)MT.1943-5533.0002154

[30] V. Marcos-Meson, G. Fischer, C. Edvardsen, T.L. Skovhus, A. Michel, Durability of Steel Fibre Reinforced Concrete (SFRC) exposed to acid attack – A literature review, Construction and Building Materials 200 (2019) 490-501 https://doi.org/10.1016/j.conbuildmat.2018.12.051

[31] F.A. Silva, A. Peled, B. Zukowski, R.D.T. Filho, Fibre Durability, in: G.P.A.G. van Zijl, V. Slowik (Eds.) A Framework for Durability Design with Strain-Hardening Cement-Based Composites (SHCC), Springer Berlin Heidelberg, 2017, pp. 68 - 69. https://doi.org/10.1007/978-94-024-1013-6.

[32] H. Zhu, D. Zhang, Y. Wang, T. Wang, V.C Li, Development of self-stressing Engineered Cementitious Composites (ECC),Cement and Concrete Composites 118 (2021) 103936 https://doi.org/10.1016/j.cemconcomp.2021.103936

[33] A.M. Neville, Properties of Concrete, Longman, London, 1995

[34] M. Li, V.C. Li, Behavior of ECC/concrete layer repair system under drying shrinkage conditions, www.researchgate.net/publication/228617167, 2011(Assessed April 2023).

[35] E.H. Yang, Y. Yang, V.C. Li, Use of high volumes of fly ash to improve ECC mechanical properties and material greenness, ACI Materials Journal, 104 (6) (2007) 303-311

[36] M.E. Karagüler, M.S. Yatağan, Effect of aggregate size on the restrained shrinkage of the concrete and mortar. MOJ Civil Eng. 4(1) (2018) 15–21. https://doi.org/10.15406/mojce.2018.04.00092

[37] G. A. Keoleian, A. Kendall, J.E. Dettling, V.M. Smith, R.F. Chandler,M.D. Lepech, V.C. Li, Life cycle modeling of concrete bridge design: Comparison of engineered cementitious composite link slabs and conventional steel expansion joints, Journal of infrastructure systems, 11(1) (2005) 51-60.

[38] J. Tian, X. Wu, Y. Zheng, S. Hu, Y. Du, W. Wang, C. Sun, L. Zhang, Investigation of interface shear properties and mechanical model between ECC and concrete, Constr. Build. Mater. 223 (2019) 12-27 https://doi.org/10.1016/j.conbuildmat.2019.06.188

[39] S. Gao, X. Zhao, Q. Jinli, Y. Guo, G. Hu, Study on the bonding properties of Engineered Cementitious Composites (ECC) and existing concrete exposed to high temperature, Constr. Build. Mater. 196 (2019) 330-344 https://doi.org/10.1016/j.conbuildmat.2018.11.136

[40] B. Wang, S. Xu, F. Liu, Evaluation of tensile bonding strength between UHTCC repair materials and concrete substrate, Constr. Build. Mater. 112 (2016) 595-606 https://doi.org/10.1016/j.conbuildmat.2016.02.149

[41] M. Şahmaran,H.E. Yücel, G. Yildirim, M. Al-Emam, Investigation of the Bond between Concrete Substrate and ECC Overlay (2014) https://doi.org/10.1061/(ASCE)MT.1943-5533.0000805

[42] M. Mo, V. Li, The influence of surface preparation on the behaviour of ECC/concrete layer repair system under drying shrinkage conditions, https://www.researchgate.net/publication/268424297, 2016 (Assessed April 2023).

[43] Y. Zhang, S. Bai, Q. Zhang, H. Xie, X. Zhang, Failure behavior of strain hardening cementitious composites for shear strengthening RC member, Construction and Building Materials, 78 (2015) 470-473 https://doi.org/10.1016/j.conbuildmat.2015.01.037

[44] G. Wang, C. Yang, Y. Pan, F. Zhu, K. Jin, K. Li, A. Nanni, Shear behaviors of RC beams externally strengthened with engineered cementitious composite layers. Materials, 12(13) (2019) 2163. https://doi.org/10.3390/ma12132163

[45] J. Wei, Y. Chen, C. Wu, C.K.Y. Leung, Shear strengthening of reinforced concrete beams with high strength strain hardening cementitious composites (HS-SHCC). Mater Struct, 53 (4) (2020) https://doi.org/10.1617/s11527-020-01537-1

[46] X. Wu, T.H.-K. Kang, Y. Lin, H.-J. Hwang, Shear strength of reinforced concrete beams with precast High-Performance Fibre-Reinforced Cementitious Composite permanent form. Compos Struct, 200 (2018) 829-838. https://doi.org/10.1016/j.compstruct.2018.06.007

[47] X. Shang, J. Yu, L. Li, Z. Lu, Shear strengthening of fire damaged RC beams with stirrup reinforced engineered cementitious composites. Eng Struct, 210 (2020) 110263 https://doi.org/10.1016/j.engstruct.2020.110263

[48] R. Li, M. Deng, H. Chen, Y. Zhang, Shear strengthening of RC shear-deficient beams with highly ductile fibre-reinforced concrete, Structures, 44 (2022) 159-170 https://doi.org/10.1016/j.istruc.2022.08.013