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INNOVATIVE MATERIAL FOR TUNNEL SEGMENTS

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ABSTRACT

Based on the idea of taking advantage of the Functionally Graded Material (FGM) concept, new precast tunnel segment materials called layered Functionally Graded Concrete (FGC) have been developed by combining mixtures of different compositions by using different processing techniques. Nevertheless, for segments in addition to the layer processing Functionally Graded Concrete (FGC) problem of keeping the interface stability under different load combinations the production of a thin and regular interface thickness are a commonly regard as leading influence factor for the structural element performance. In this paper, the benefits in terms of global section performance when using different SCC mixture combinations are evaluated under compressive tests on cubic specimens prior and after being exposed to different aggressive environments or ISO fire test while the interlayer robustness was evaluated also under splitting test on some selected specimens. Based on the collective literature processes survey and test findings it was concluded that layer processing Functionally-Graded Self Compacting Concrete (FGSCC) elements, show promise for making most cost-efficient multifunctional cement composite structural cross-sections. Results showed the potentiality of this concept in reducing: i) material costs, and ii) the design or processing throughputs.

1 INTRODUCTION

One of the main problems of the outer side of underground tunnel linings is that almost all rock and soil contains water draining from above (seepage) or penetrating from below, being in some cases under pressure [1]-**Error! Reference source not found.**. On the other hand, fire in the case of transport tunnels, because of almost recent events, is now a major concern which can affect the lining inner side **Error! Reference source not found.**-[7]. Moreover in the case of segmental tunnels the on-site assembly introduces thrust force induced by the Tunnel Boring Machine, and consequently the effect of load concentration and splitting phenomena can strongly contribute to shorten even more lining service life if both inner and outer sides are damaged **Error! Reference source not found.**, [7]. Although, each particular problem needs of different mixture design considerations currently in precast tunnel segments a single monolithic high performance mixture is adopted [8]-**Error! Reference source not found.** in an attempt to optimize the aforementioned objectives (multifunctionality) by balancing the different trade-offs by means of a mix design involving a single fibre type [6]-[7] or fibre cocktails [8]. But, this significant state of art technology [8] entails an inappropriate use of resources and higher supply costs [9]-[10] and may not meet always all the performance criteria desired for the design.

An alternative innovative approach that can maximize the performance while minimizing the cost of the concrete segments is to use layers with different properties at specified depths **Error! Reference source not found.**, [9]-[19]. By having continuous functional layers (or graded) the performance criteria of each layer can be maximized by including them only in the necessary location with the appropriate thickness **Error! Reference source not found.** to address the multiobjective performance. For example, a different type of aggregate could be used to improve the inner fire resistance [7][19] while the outer and inner surface layers could contain steel fibres in order to improve their toughness and/or in the case of outer healing capacity**Error! Reference source not found.**[14]. Potentially, this functionally graded concrete system could outperform similar but using less material to an existing homogeneous concrete material layer [8] in terms of strength, durability, fire resistance and life cycle costs.

The research, design, and manufacturing of functionally graded materials –FGMs- have been extensively applied to high-performance materials such as graded metals or composite metals–ceramics for high-technology applications [12]-[13]. Building layered elements is not a new concept in the cement composites construction industry also as the functionally graded concrete (FGC) concept was used for improving the corrosion resistance [14], for optimizing fibre quantity distribution [15]-[18], for solving thermal insulation [19] and also for the particular case of manufacturing FG concrete tunnel segments [10]. Nevertheless, the concept need of further improvements as majority of these solutions mean complex design and/or “graded processing” throughputs [14][18] or graded processing which does not allow an accurate determination of the transition area [10][19]. Moreover, the primary objectives of these previous multilayered concrete segment systems were reduced life cycle costs and improved surface capacity. Limited research was conducted to test and analyse the layer transition or in maximizing layer depths by minimizing these of interlayers.

The objective of the research was to explore the structural benefits of using SCC [20] technology for improving the FGC concept for precast segments by testing and simulating the fracture behaviour under compressive forces for different combinations of layered plain and fiber-reinforced SCC materials or plain and plain SCC with different aggregates composition subject to different tunnel environmental conditions **Error! Reference source not found.**. By achieving this objective, this specific research demonstrated the viability of the synergetic of FGM and SCC concepts [9] named as FGSCC (Functionally Graded Self Compacting Concept) and proposed key concepts required for modelling and designing multilayered SCC segment systems using a FGC layering method for pre-cast tunnel segments. It was noticed [12] that layering method is considered sometimes insufficient for producing FGM because it leads to the formation of sharp interfaces between layers and an adhesive sectional failure. Moreover, considering that SCC allows also an effortlessly casting of sections the synergy would result in a real step forward considering other layered Functionally Graded Concrete solutions [10][19].

2 EXPERIMENTAL PROGRAMME

The testing program consisted of the eight series shown in Figure 1. Three cubic samples replicates were made for each material configuration. While the materials used for each layer are defined in accordance with the mixture identifications (Mixture ID) of Table 1. Series I-III where all one layer samples (monolithic) the testing specimens of series IV to VII where designed to analyze the effect of using either plain SCC of different strength class (IV) or plain SCCs and FRSCCs as part of the top (V) or bottom casted layers (VI, VII,VIII).

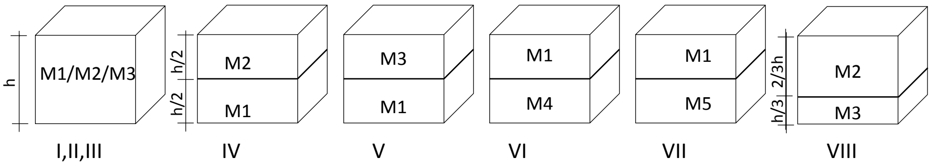

Figure 1. Material combinations used in experimental program

Table 1. SCC Mixture proportions and main properties of layer materials used in experimental Program

Mixtures ID / Material	M1	M2	M3	M4	M5
	Kg/m^3				
CEM I 42,5R	400	-	-	554	400
CEM I 52,5R	-	500	500	-	-
Limestone filler	150	50	50	-	47
Silica fume	-	45	45	-	-
SA (0-4 mm)	959	858	858	1663	800
SA (4-10 mm)	632	694	694	-	-
Vermiculite	-	-	-	-	42
Perlite	-	-	-	-	13
Steel Fibres	-	-	80	-	25
PP Fibres	-	-	-	11.1	-
SP1	6	-	-	5.5	6
SP2	-	10	13	-	-
w/c ratio	0.4	0.35	0.35	0.45	0.45

Properties						
Fresh	S (mm)	670	620	600	600	590
	T50 (s)	6	7	8	8	8
28 days	f_c (MPa)	60±0.9*	87±1.1*	85±1.5*	45±1.9*	17±1.6*
	E_c (GPa)	37.5**	40.1**	40.5**	22.5**	15**
	f_{ct} (MPa)	-	6.8±0.6*	9.9±0.9*	-	-

*average of 3 samples. ** individual value

Compressive test specimens (series I and IV-VII) were tested as shown in Figure 2 left, to known the ultimate strength values of the functionally layered SCC materials in comparison with the average of those obtained from the individual samples of series I (considered as reference). The concrete fracture pattern was also analysed. Moreover, splitting test specimens (series II, III and VIII), as shown in Figure 2 right, to characterize the fracture of the individual and functionally layered SCC materials having a similar strength and porosity **Error! Reference source not found.**.

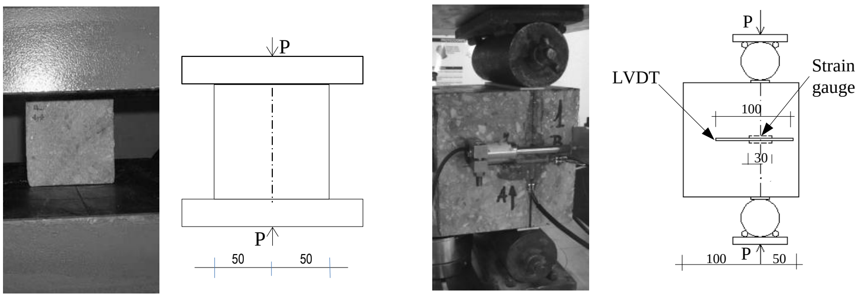

Figure 2. Test setups for layered FGSCC specimens: compressive (left) and splitting (right) tests. Dotted line represents the graded zone as the samples were placed perpendicular to the casting position

2.1 Mix design and properties

The main solid components used for preparing the different SCC mixtures (M1-M5) were: two Portland cement types (CEM I 42.5R and CEM I 52.5R); limestone filler (fineness of 78,8% < 63µm); fine and coarse siliceous aggregates (SA) of grading 0-4 and 4-10 mm respectively, silica fume (SiO2 > 92%), and two types of high range water reducer admixture having 35% of solids content (Viscocrete 3425–SP1 and 5th generation Viscocrete TSG 30–SP2). Furthermore, hook-ended steel fibres (diameter = 0.55 mm and length = 30 mm) -SF-, polypropylene fibres (diameter = 0.015 mm and length = 6 mm) -PPF- and lightweight aggregates (LWA): Vermiculite of grading 0-4 mm and Perlite of 0-1.5mm were adopted. The fibre dosage of the FRSCC mixtures was in all the cases in agreement with the amounts practically used by engineers in the field.

The plain- and FR-SCC batches were mixed at approximately the same time in an IB37-010E concrete mixer of capacity 50l. After testing the accomplishment of their fresh properties (standard EN test method for slump flow of SCC) 4 standard cylindrical specimens of ∅150x300 mm were cast for testing at the age of 28d their main mechanical properties such as compressive strength (f_c), tensile strength (f_{ct}) and elasticity modulus (E_c). Rheological and 28d results of each of the SCC mixtures are shown in Table 1. The addition of fibres did not affect the compressive strength and elasticity modulus of the plain concrete, but the higher fibre content mixtures resulted in slightly increased of split tensile strength over plain concrete, a result that is typically seen when fibre contents approach 1% **Error! Reference source not found.**[18].

2.2 Sample preparation

Bulk and Layered samples of 100x100x100 mm (series I and IV to VII) or of 150x150x150 mm (series II, III and VIII) were produced using the mixes described in Table 1 following strictly the order which is shown in Figure 1 from bottom to top, which in turn involves always a mixture with higher packing density content at the top. This order is also the needed one to follow for casting a tunnel segment as the form side which it is in coincidence with the inner part of lining is always placed at bottom. All layered specimens shown in Figure 1 were made by first casting the bottom layer (Material M1 in Figure 3 left) up to specified depth of 50 mm. The top layer (Material M2 in Figure 3 right) was then placed into the form, approximately 15 minutes later. The self-consolidation of the top layer (Material M2) included 3-5 mm penetration **Error! Reference source not found.** into the bottom layer (Material M1) that would be enough to ensure the graded interface zone between the two materials.

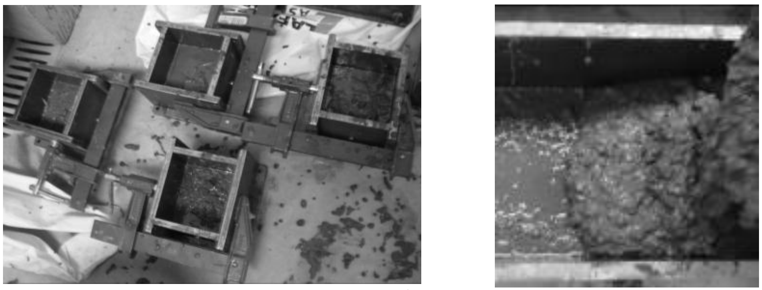

Figure 3. Example of series S2 casting: (left) After 1st layer has been cast; (right) During the 2nd layer placement

Although the whole testing programme involves different curing regimens and different exposed conditions **Error! Reference source not found.**, [7], **Error! Reference source not found.**, all series specimens included herein, were those subjected only to standard curing conditions in climatic chamber (20º±2ºC, RH=98±2%) up to the age of testing (28 days). One exception were the samples of series VI and VII, which were tested all (those kept at lab conditions and those subject to ISO test) after performing the fire test approximately at the age of 5 months. Regarding fire test they were performed as it was described in **Error! Reference source not found.**, [7] with only the bottom surface of the specimens exposed to the fire.

2.3 Testing procedure

Preliminary quality control: Prior to be tested specimens and each of the layers were naked-eye observed and then measured by using a digital calibre. After visual inspection, no surface micro-cracking or other defects have been observed in any of them either on the whole element or in the interlayer area. Results showed also that all specimens met their element and layers length design criteria (100±1mm or 150±1mm, 50±1mm). Moreover, the interlayer, was in all of the cases between 3-4±0.4mm. Layer interface were observed at stereomicroscope (x2.5) by examine cut surfaces of samples randomly taken after testing.

Compressive test (CT): the tests were carried out on hydrostatic testing machine capable of applying load continuously at the rate of 0.03kN to 45kN/s with a maximum load capacity of 3000kN. The tests were performed as it is described in the EN 12390-3 standard [21]. Thus, all the cubes were tested on the face perpendicular to the casting face (see Figure 2 left). During the test the compression machine exerted a constant progressing force on the cubes till they fail, the rate of loading is 0.6 ± 0.2 M/Pas (N/mm^2/s) and the maximum compressive strength that read at failure. Once the cubes have reached failure, the failure shape of the cube has been checked to determine whether it's a satisfactory/unsatisfactory failure in the case of monolithic samples or similarities/differences to the monolithic samples in the case of layered samples.

Tensile splitting test (ST): The test was performed as it is described in the 12390-6 standard [21] with the only difference that the load was applied in correspondence with the transition zone of the series VIII samples, as shown in Figure 2right. In the remaining series (bulk or series II and III samples), the load was also applied at the same position. Normal deformations were recorded at the center of the height using both electrical resistance strain gauges and LVDTs, placed on the opposite faces as shown also in the figure. Additionally, in plane strain gauges were placed but these measurements are not included on this paper. The strain gauges had 30 mm length, a resistance of 120±0.3 Ω and a factor of 2.11±1 % while the LVDTs had 100±5mm. The tests were conducted, by applying the load continuously at the stress rate of 0.05 N/mm^2.s, on the same universal hydraulic testing machine, up to failure of sample. As in the previously described test the load displacement-diagram was produced digitally as the test proceeded.

3 RESULTS AND DISCUSSION

3.1 Compression performance

Figures 4 show the different shapes obtained once the different cube series have reached the compressive failure (Figure 5). As it is possible to see, the sample I.1, selected as representative of series I (adopted as reference), presents a pyramidal failure shape (Figure 4a) similar to those referred on the EN standard [21] as explosive satisfactory failure. The maximum loads of the samples of series I was higher than the design ones in all cases as it is shown in Figure 5 where the average values of each series are presented. The Series IV, which combines two strength class plain SCCs, as well as the series V, which combines a plain and a fibre reinforced SCCs of different strength class maximum loads present in general different type of failure although for both series the increasing in strength were similar and about a 24-27% higher.

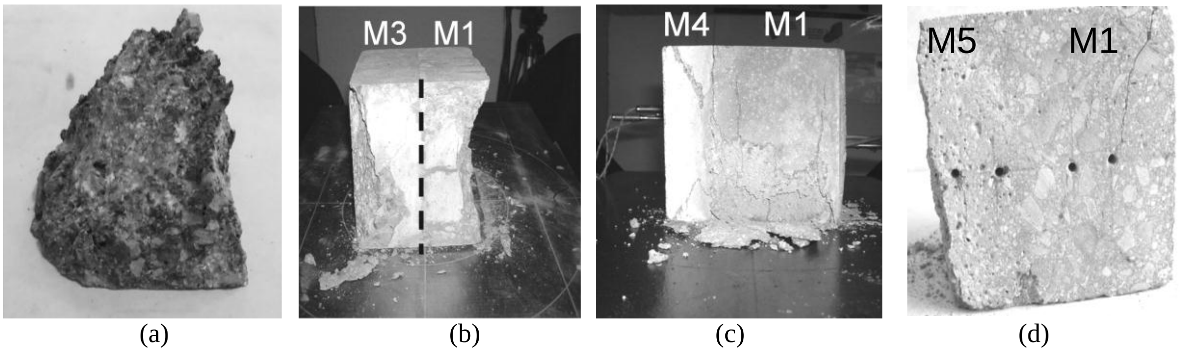

Figure 4. Failure presented by the: (a) I.1 sample, (b) V.II sample (c) VI.3 sample and (d) VII.3 sample

While in the case of materials with and without fibres the type of failure was for all the cases similar to the one shown in Figure 4b, in the case of series IV the failure was similar to the one presented by M1 in the Figure 4b for both materials. This was due not only to the use of a higher strength material in the FGSCC composition of series V but also due to the use of fibres.

In the case of Series VI and VII the failure values were lower (5 and 15% respectively) due to the use of a non-structural material and light weight aggregates (M4 and M5) as part of the FGSCC solutions. On the samples of series VI and VII after being exposed to fire (or series VIf and VIIf) the failure were similar to this shown in Figure 4c and 4d respectively, while failure values were 27% and 25% less than those of same series not exposed to fire, but in any case with an improved mechanical behaviour after fire if comparing with series I after fire (or series If) which exhibited a strength loss of 38%.

It is noteworthy to emphasize that the interlayer bond in all cases remained unbroken (also for those samples tested after fire tests) and the elements show a cohesive (monolithic) failure which confirms that the multilayer FGSCC as designed can be classified as a FGM. Thus, results showed the good interface bond although the graded area is much lower (for all the cases) than that referred by other authors [10][18][16] and also the advantages of a FGC. This can due to the use of mixes with high workability and high packing density as it is the case of the SCC mixes.

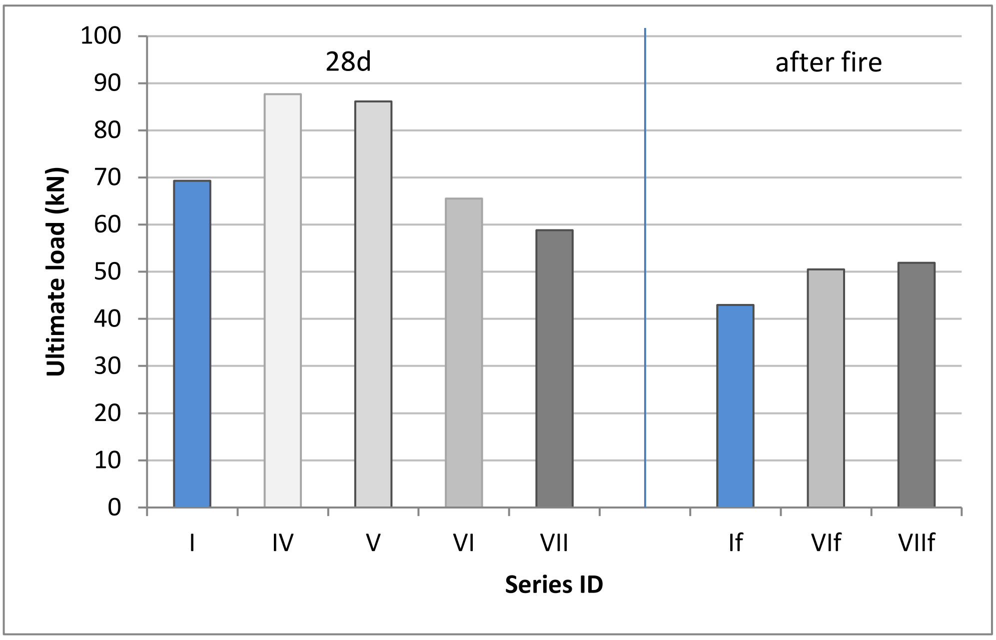

Figure 5. Average ultimate load of samples of control series (I) and layered series IV-VII. Samples If, VIf and VIIf correspond to samples exposed prior to ISO curve test

3.2 Tensile splitting performance

For almost all the series, the results indicate that the material behaves elastically linear until first peak load is reached. After this point, the samples of series II fail suddenly, while in those of series III the load stabilizes at this level before increasing again with an increase deformation until a second peak load is reached (Figure 6). Moreover, the first peak value is about 6% higher for the steel fiber reinforced materials (Series III) than for those without fibers (Series II) although SCC compressive strength were quite similar for both cases (Table 1). In the case of FG samples, material follows a similar trend than those of series III up to the first peak, then it continues with the same trend up to a sudden failure occurs for a load higher than this of the series III first peak load (Figure 6). Thus, it seems that FG samples present an improved behavior in comparison to those of series II (bulk without fibers).

In relation to the type of failure of the FG samples, it was the one presented on Figure 7 for the analyzed cases. As it is possible to observe, failure does not occur only along the loading axis, but combining a failure in this plane with other that cross the vertical axis with an angle of 5 degrees approximately. Thus, the failure of FG samples is quite different from those of series II (SCC without fibers), that it was vertical and along the loading axis as it is expected for such cases. It was also different from those of fiber reinforced SCC (series III) that presented more than one distributed and vertical main crack[22].

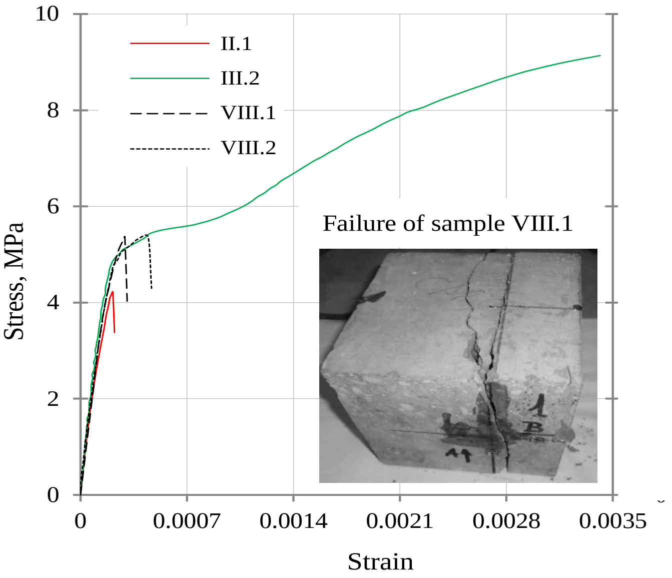

Figure 6. Stress-strain relationship of the samples of the series II, III and VIII at 28 d (splitting test)

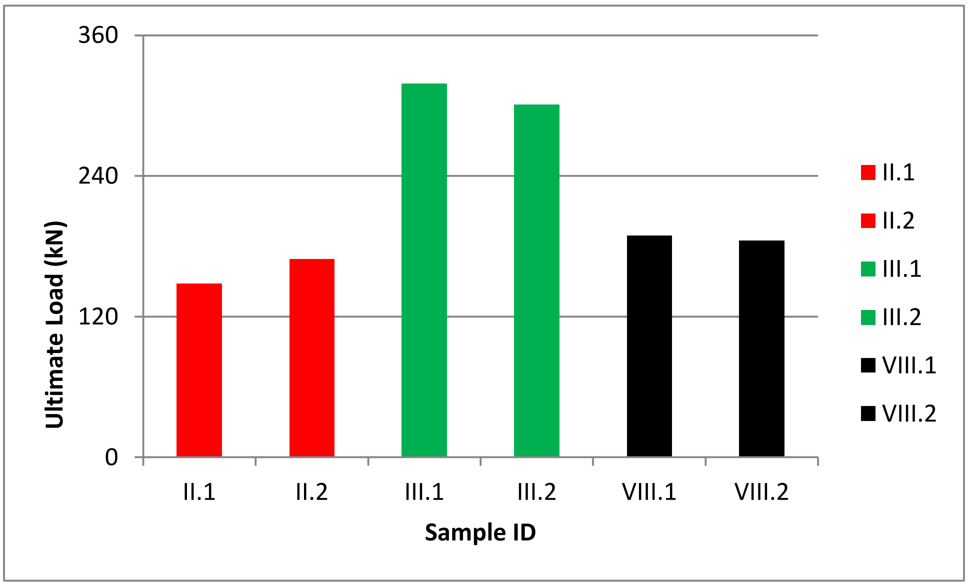

Figure 7. Ultimate load of the samples of the series II, III and VIII under tensile splitting test at 28 d

The analysis of the type of failures would have been interesting, even though the extremely small number of FG splitting tensile tested samples available up now would not allow a correct and deep study in this sense. Nevertheless, it seems that interface-FG, as it was cast, contributes to avoid occurring of a sharp failure.

4 CONCLUSIONS

In this paper, an innovative material FGSCC using mixes when combining suitable for tunnel segments has been presented and the following conclusions can be drawn:

- Compared to the bulk, FGSCC samples have almost similar strengths under compression test when a fiber reinforced SCC with lower strength forms part of the FGSCC solution and almost equivalent to the one of higher strength class under compressive tests.
- The examination of the samples by the selected compressive and tensile tests demonstrates that the interface or graded area is not the weakest section. On the contrary under splitting test the FGSCC has failed where the weaker tensile strength material was and not by adhesive failure of interface even though the loading was applied directly on the interface
- Initial deformations (elastic modulus) were similar under tensile splitting tests for the different solutions.
- The successful outcomes of functionally graded samples have proved the feasibility of FGSCCC concept and would be the most sustainable and cost-efficient solution for further applications.

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