MECHANICAL AND DURABILITY ASSESSMENT OF CONCRETES OBTAINED FROM RECYCLED ULTRA HIGH PERFORMANCE CONCRETES

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ABSTRACT

The aim of this work is to analyse the mechanical and durability properties of Recycled Ultra High Performance Concretes (RUHPC) containing different amounts of recycled fine aggregate obtained from crushing Ultra High Performance Concretes (UHPC). This paper summarizes and compares the results from different experimental campaigns carried out in the framework of the ReSHEALience project (Rethinking coastal defence and Green-energy service infrastructures through enhanced-durAbiLity high-performance cement-based materials) which has received funding from the European Union's Horizon 2020 programme (GA 760824). Mechanical performance was evaluated by means of compressive and flexural tests, whereas durability was evaluated by means of chloride penetration, chloride migration and water absorption capillary tests. The results indicated that replacing 50% or 100% of natural aggregates with recycled aggregates did not significantly affect neither compressive strength nor flexural strength. In the case of high replacement rates, a slight decrease in workability was detected, but the mix retained its self-compacting properties. RUHPC had similar durability performance as UHPC. In conclusion, the results have shown that it is feasible to produce RUHPC; the recycled fine aggregate has shown great potential to be used in the production of new UHPC. Scalability of the recycling procedure to industrial level was also addressed in order to pave the way towards the uptake from the different value chain actors of the construction industry of the innovation potential demonstrated by the research.

KEYWORDS: High Performance Concrete, recycled aggregates, durability.

1. INTRODUCTION

Construction industry is one of the most important consumers of raw materials and hence one of the main responsible of CO_2 emissions. Moreover, it is one of the main producers of waste: as a matter of fact, the Construction and Demolition Waste (CDW) signify 30-40% of solid waste produced in the world [1, 2]. This is due on the one hand to the renovation of buildings that are not anymore adequate, neither from the structural nor from the energy point of view, as well as, on the other, to the degradation of materials and reduced structural performance experiences because of aggressiveness and increasing challenges by structural service scenarios [3]. In this framework, concrete represents about a 67% of the total CDW in the US whereas in Europe CDW quantities are linked to the population density and the Gross Domestic Product of each single country [4]. This motivates an increased interest to use CDW through construction and demolition.

Recycled aggregate concrete (RAC) can be used for structural and non-structural purposes and can be classified in recycled concrete aggregate, recycled brick aggregate and recycled mixed aggregates. Recycled aggregates (RA) can be used not only for producing concrete but also for other application such as pavements, roadways and other cementitious composites [5]. Standards indicate minimum requirements for their application, including maximum percentage of crushed concrete, minimum bulk density and maximum absorption capacity [6, 7]. Recycled aggregates have higher water absorption, lower density, lower crushing strength and abrasion resistance compared to natural aggregates. On the other hand, the properties of RAC are affected by the replacement ratio of recycled to natural aggregates, but also by the performance of the concrete from where RAs were obtained. This replacement also influences the mechanical performance of RAC, where generally compressive strength is more influenced than tensile and flexural strength. Reduction in compression can reach up to 30%, for 100% of replacement of aggregates [8].

One of the objectives of ReSHEALience project [9] is to analyse the potential for recycling of UHPC mixes formulated and validated in real applications UHPC mixes, in cradle-to-cradle approach, using the recycled UHPC obtained from a UHPC previously casted and studied in the project. As a matter of fact, UHPC is a relatively new category of construction materials, and the actual possibility for its recycling may look remote since it is also claimed as a longer lasting material because of its higher durability in both the un-cracked and cracked state [10, 11]. Anyway, addressing its recyclability potential has to be meant as a new significance to longer lasting construction materials and structures, moving, also in structure and infrastructure, from an “additive” concept, where new additions are built adjacent to the existing ones to comply with new needs and demands, to a circular concept, where the structure and infrastructures can be self-regenerated and rebuilt to be adapted to new context needs and demands, according to a new concept and using to the largest possible extent its own materials, without any expect loss of performance as if built with “freshly” produced materials employing 100% new raw resources.

2. OBJECTIVES

The mechanical and durability properties of Recycled Ultra High Performance Concretes (R-UHPC) containing different amounts of recycled fine aggregate obtained from crushing Ultra High Performance Concretes (UHPC) have been analysed in this paper. This paper summarizes and compares the results from different experimental campaigns carried out in the framework of the ReSHEALience project. One of the campaigns were carried out by University of Malta (UoM) and Politecnico di Milano (PoliMi) whereas the second campaign was carried out by the Universitat Politècnica de Valencia (UPV). Photos of the recycled constituents (aggregates and fibres) obtained from the recycled UHPC are shown in Figure 1.

3. UOM-POLIMI EXPERIMENTAL CAMPAIGN

The recycled UHPC concrete (R-UHPC) was obtained from a four-month-old UHPC with an average compressive strength of 150 MPa. The original UHPC was crushed and processed in the laboratory using a jaw crusher (Pascal Engineering) operating at a power of 750 W. Repeated crushing was required in order to reach the finer size of aggregate required to produce UHPC, and to completely separate the steel fibres from the concrete matrix. A magnet was used to remove steel fibres. A sieve analysis was performed on the crushed material up to obtain a grain-size distribution curve similar to that for the natural aggregates used in the original UHPC.

Figure 1. Photos of the recycled aggregates (left and centre) and fibres (right) obtained from recycling UHPC.

3.1. Mix design

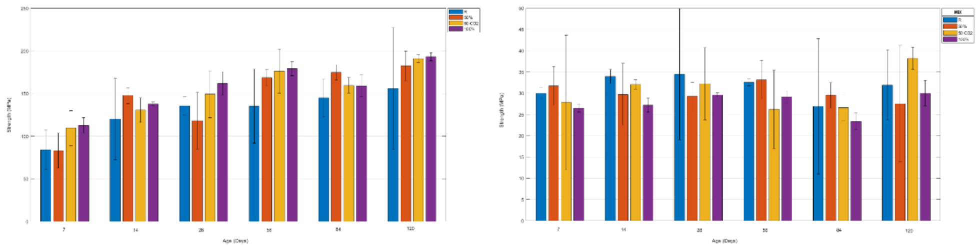
The UHPC mix composition used as reference has been formulated, validated and produced at the UoM, in the framework of the ReSHEALience project to be employed in the retrofitting of the column support structure of an elevated water tank in the Valletta Grand Harbour, one of the pilots of ReSHEALience [9]. The concrete mixes shown in Table 1 used different replacement percentages of natural aggregates by recycled ones: 0% as reference, 50% R-UHPC and 100% R-UHPC, moreover a mix with 50% of recycled carbonated aggregates was produced. Carbonated aggregates were prepared using an accelerated carbonation chamber set with a temperature of 25°C and 65% Relative Humidity, under accelerated conditions with a CO_2 concentration of 100%.

Table 1. Mix design proportions for different types of mixture investigated at UoM

Constituents(kg/m^3)	Reference	50% R-UHPC R-UHPC-C	100% R-UHPC
Cement 52.5 R	700	700	700
Silica Fume	400	400	400
Superplasticizer (ACE 442)	64	64	64
Water	231	231	231
Natural aggregate 117/F	286	143	0
Natural aggregate 103	409	205	0
Natural aggregate 113	122	61	0
Recycled aggregate	0	409	817
Steel fibres (l_f = 22 mm, d_f = 0.2 mm)	160	160	160
Crystalline admixture (Penetron Admix ®)	5,6	5,6	5,6

3.2. Mechanical performance of recycled UHPC (R-UHPC)

The mechanical properties (compressive and flexural strength) of UHPC and R-UHPC were determined at 7, 28, 56, 90 and 120 days. Results are shown in Figure 2 and Figure 3. To this purpose three prismatic specimens 40 x 40 x 160 mm were casted for each mix and tested in flexure. Then the six broken halves were tested in compression. From Figure 2 it can be observed that specimens made with R-UHPC showed higher strength values compared to UHPC, even for larger percentage substitution of natural aggregates. This could be attributed to increased presence of un-reacted cement particles in the finer portion of the recycled aggregates. This also resulted into the evidence that replacement of natural aggregates with recycled ones did not substantially alter the flexural strength capacity and its development over time. The variation is acceptable and it is in accordance with the effects of dispersed fibre reinforcement. Moreover, the concrete with 50% of carbonated recycled aggregates (R-UHPC-C) did not show significant differences as compared to the non-carbonated ones.



(a) Compressive strength (b) Flexural strength

Figure 2. Mechanical properties (compressive and flexural strength values) for UHPC and R-UHPC

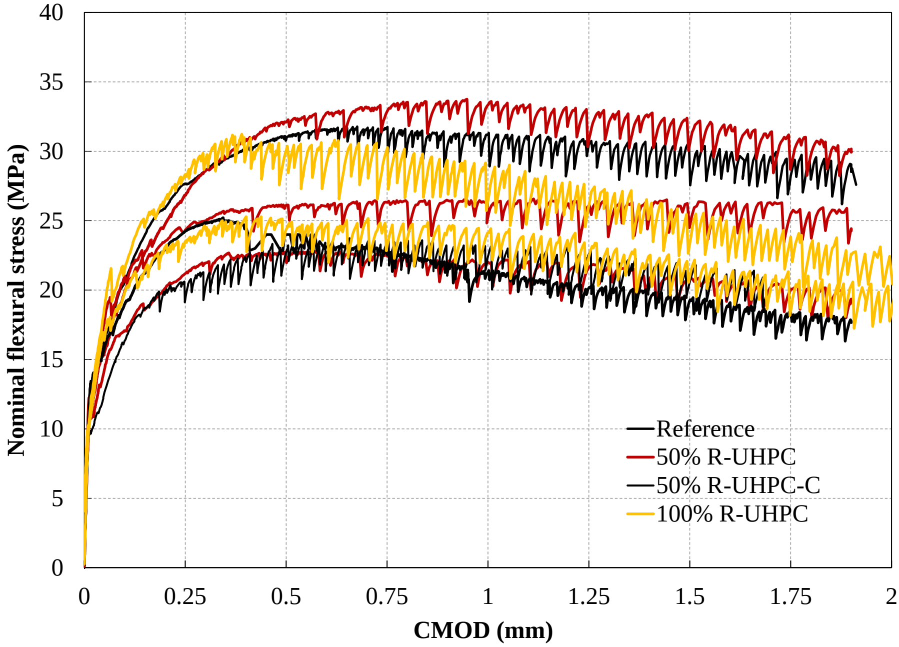


Figure 3. Flexural stress curves versus CMOD for UHPC (reference) and R-UHPC (50%, 100% and carbonated)

3.3. Durability properties of recycled UHPC (R-UHPC)

Durability was evaluated by means of water absorption capillary tests, chloride penetration and chloride migration. Sorptivity tests were carried out at different ages on 40x40x160mm prismatic specimens based on EN 13057. To this purpose, the specimens were first dried at 40ºC up to constant weight and then kept in laboratory conditions for 24h. The lateral surface was waterproofed with silicon up to 20mm depth from the intrados face and then were immersed in a water basin. The water uptake was measured by weighting the specimens at several intervals for 24h. The water uptake was plotted versus the square root of time, the sorptivity coefficient [kg/(m^2 $h^{0.5}$)] was determined as the slope of the curve. At 28 days, all concretes showed similar sorptivity coefficients, only the mix with 50% of recycled carbonated aggregates (R-UHPC-C) showed a higher value. Sorptivity coefficients decreased with aging time as shown in Figure 4 and were very similar for all the analysed mixes.

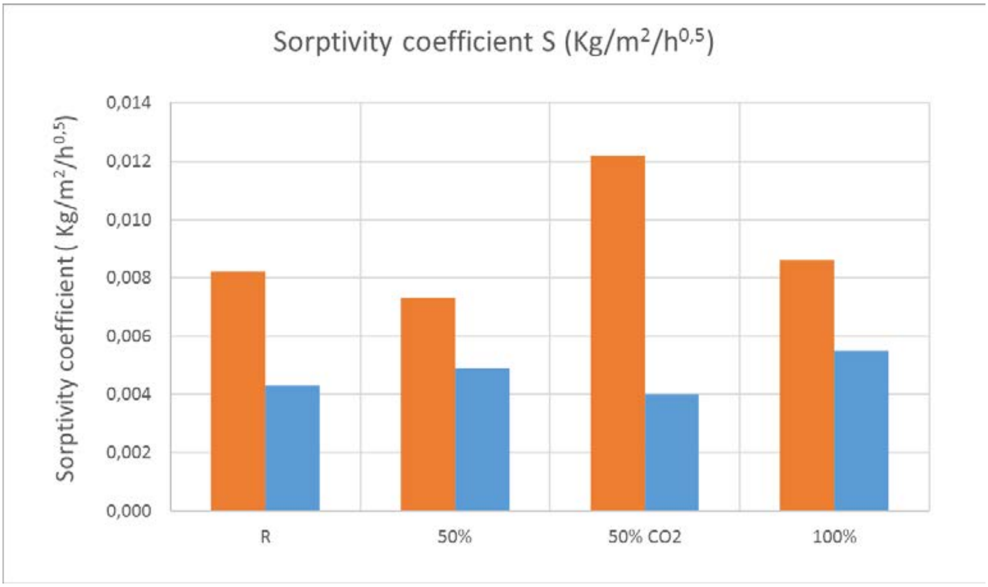
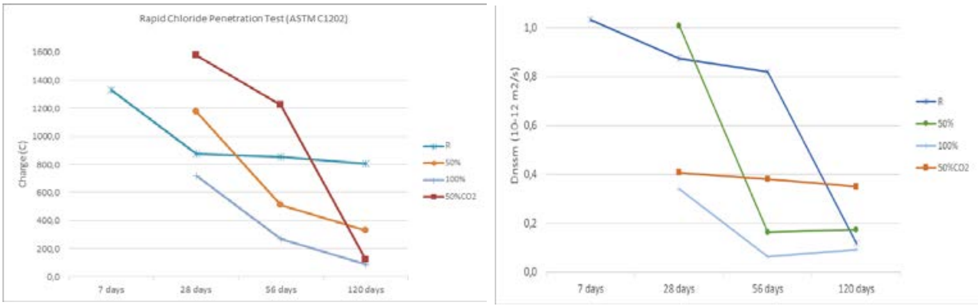


Figure 4. Sorptivity coefficient for the different investigated mixes at 28 and 120 days

The Rapid Chloride Ion Penetration test (RCPT) was carried out for all mixes after 28, 56 and 120 days, based on ASTM C1202-97. As shown in Figure 5a, it is observed a significant improvement with time in the performance of the recycled UHPC specimens as compared to reference ones since, ASTM C1202 considers "very low" chloride ion penetration for values of passing charge between 100 and 1000 coulombs. A continuous decreasing trend for lower charge is observed, obtaining the minimum value at 120 days for all mixes, especially the recycled ones (R-UHPC). Moreover, chloride migration tests were carried out based on NT Build 492. To this purpose, cylindrical specimens (Ø100mm, h=50mm) were analysed at 28, 56 and 120 days. For each age, the chloride penetration depth was determined and subsequently, the non-steady state chloride migration coefficient (D_{nssm}) was determined (Figure 5b). Figure 5b shows that D_{nssm} decreases with the age for all concrete mixes. In conclusion, the results from the chloride penetration tests support the potential of the exploitation of recycled UHPC for the production of UHPC.



(a) Rapid Chloride Ion Penetration (RCPT) test (b) Chloride migration coefficient

Figure 5. Chloride Penetration in R-UHPC

4. UPV EXPERIMENTAL CAMPAIGN

UPV collaborated with the recycling plant "Gestión y Reciclaje Belcaire" in Moncofa (Castelló) to test the process industrially, which allowed to recycle around 2 tons of UHPC. The process allowed to obtain recycled aggregates of reduced size (< 6 mm) and separated most of the steel fibres contained in the original UHPC mixes. At the UPV laboratory, the aggregates were further sieved and classified to obtain fractions with controlled size distribution for obtaining a R-UHPC with a size distribution as similar as possible to the original mixes. Additionally, fibres where further separated using a magnet.

4.1. Mix design

UPV studied 8 mixes replacing 50% and 100% of two fractions of the aggregates and steel fibres. The replacement rates selected were 50 and 100% to evaluate the effects of high volume replacements to produce UHPC. Recycled fibres had a certain fraction of recycled aggregates strongly attached to them and thus, a correction was made to consider this content in the mixes including recycled fibres. The composition of all the mixes is shown in table 2.

Table 2. Mix design proportions for different recycled UHPC mixes.

kg / m³	*Ref*	*Fine sand*		*Medium sand*		*Fibres*		*All*	
Constituent		*50%*	*100%*	*50%*	*100%*	*50%*	*100%*	*50%*	*100%*
Cement 42.5 R-SR	800	800	800	800	800	800	800	800	800
Silica Fume	175	175	175	175	175	175	175	175	175
Water	160	160	160	160	160	160	160	160	160
Silica sand - medium	565	565	565	282.5	-	565	565	282.5	-
Recycled sand - medium	-	-	-	*282.5*	*565*	-	-	*282.5*	*565*
Silica sand - fine	302	151	-	302	302	302	302	151	-
Recycled sand - fine	-	*151*	*302*	-	-	-	-	*151*	*302*
Silica sand - flour	225	225	225	225	225	225	225	225	225
Steel microfibres	160	160	160	160	160	80	-	80	-
Recycled steel microfibres	-	-	-	-	-	*80*	*160*	*80*	*160*
Plasticizer Sika 20 HE	30	30	30	30	30	30	30	30	30

Workability, compressive strength, flexural and tensile strengths were evaluated for these 8 UHDCs to analyse the feasibility of using these recycled materials to produce new UHDC. After casting and demoulding the specimens, they were stored in a standard humidity chamber at 20°C and 95% RH until testing time.

4.2. Fresh and hardened state mechanical performance of recycled UHPC (R-UHPC)

Slump flow test was used to evaluate the workability of the mixes. The diameter was measured just after performing the test, and 10 minutes later. The results in Figure 6 left show that the mix with the highest workability is the reference mix, and that 50% of replacement of one component is feasible without significant loss of workability. When the replacement ratio increases to 100%, workability is noticeably decreased, especially in the mix "100% all", where three recycled constituents were replaced at the same time.

Compressive strength was tested on 100 mm cubes at the ages of 7 and 28 days. The results (Figure 6 right) show similar results of compressive strength when replacing the commercial sand and fibres by the recycled materials, with slightly higher variation of results.

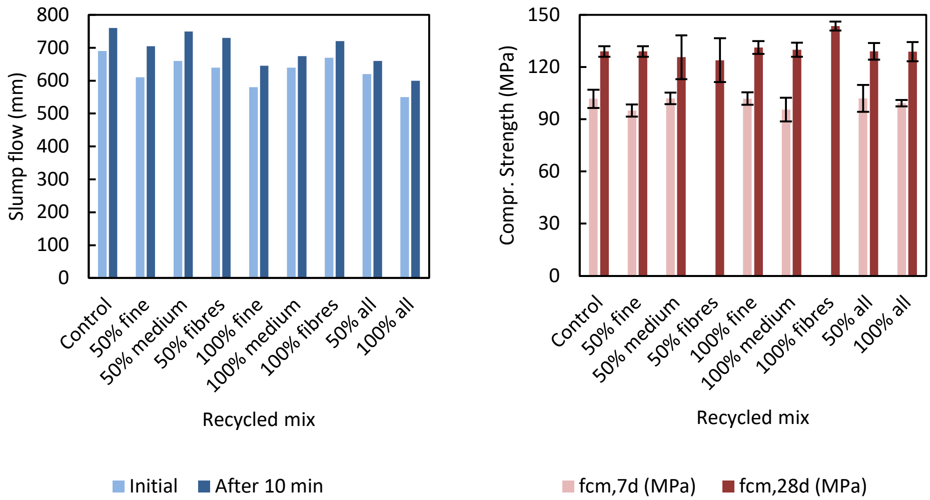


Figure 6. Slump, initial and after 10 minutes (left) and compressive strength at 7 and 28 days (right).

In addition to compressive strength, four points flexural tests (4PBT) were performed at the age of 28 days to 100×100×500 mm^3 prisms to evaluate the flexural behaviour and the tensile strength parameters of all UHPCs mixes employing a simplified inverse analysis (IA). After the flexural test, these curves have been analysed to obtain the tensile behaviour of UHPC following a simplified inverse analysis (IA) method [12]. The constitutive model is defined as a function of five parameters: elastic modulus (E), cracking strength (ft), ultimate cracking strength ($f_{tu} = \gamma \cdot f_t$) and its associated strain (ε_{tu}); crack opening at the intersection of the line that defines the initial slope to the w axis (ω_0). Table 3 shows the tensile parameters obtained for all the mixes.

Table 3. Tensile mechanical properties of the mixes.

Mix	f_t (MPa)		f_{tu} (MPa)		ε_{tu} (‰)		E (MPa)		ω_o (mm)	
	Avg	*Std.dev*	Avg	*Std.dev*	Avg	*Std.dev*	Avg	*Std.dev*	Avg	*Std.dev*
Control	9.94	*0.16*	8.26	*0.45*	4.71	*0.78*	50217	*1331*	2.68	*0.42*
50% fine	8.96	*0.72*	7.95	*0.69*	4.84	*1.21*	50250	*636*	3.44	*0.28*
50% medium	9.50	*0.33*	7.20	*0.51*	3.31	*0.97*	50650	*1626*	3.56	*0.74*
50% fibres	9.77	*0.17*	7.73	*0.78*	3.47	*2.17*	52600	*2030*	2.67	*0.79*
100% fine	9.61	*0.08*	9.62	*2.56*	3.74	*3.30*	52750	*4738*	2.67	*0.54*
100% medium	8.62	*0.31*	8.48	*0.74*	5.49	*0.62*	47500	*707*	2.72	*0.16*
100% fibres	8.31	*0.53*	6.95	*0.89*	1.55	*0.66*	51450	*5016*	1.57	*0.50*
50% all	6.95	*0.95*	6.75	*1.32*	4.71	*2.93*	48000	*2970*	2.95	*0.55*
100% all	7.49	-	5.73	-	0.73	-	46100	-	0.97	-

5. DISCUSSION

Figure 7 shows the results of the fresh properties measured by the slump flow test and compression strength at 28 days for the two experimental campaigns. The results of the slump flow test shows that the aggregates recycled obtained from UHPC are suitable to produce new UHPC since the mixes maintain the self-compacting properties. Similarly, the results show comparable results of compressive strength, reaching typical values of UHPCs, when replacing the commercial sand and fibres by the recycled materials, even when replacing completely some components.

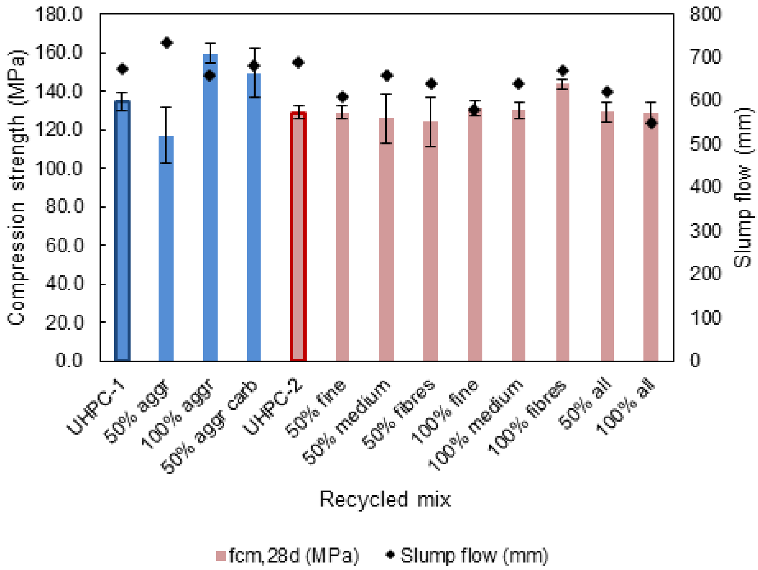


Figure 7. Compressive strength at 28 days (bars) and slump flow (diamonds) for UHPC and R-UHPC. The outlined bar indicates the reference UHPC in each experimental campaign.

6. CONCLUSIONS

The most important finding of these results obtained from the fresh and hardened states is that UHPC can be recycled to be used as aggregate in new UHPC production. This is an important step towards the re-use of waste materials originating from ultra-high durability concrete applications. More specifically, the conclusions of this study can be summarized as follows:

- The replacement of natural aggregates by aggregates recycled from UHPC did not reduce the significantly the self-compacting properties of UHPC. Slump flow slightly reduced when using increasing the replacement of recycled compounds. 50% had no effects on workability.
- Most of the UHPC mixes with recycled aggregates and fibres had a compressive strength similar to their reference UHPC mix, whereas some specimens reached higher compressive strength values probably due to the positive effect that the delayed hydraulic activity of the cement/binder paste layer surrounding the original natural sand particles.
- Flexural strength was not affected by the replacement of natural aggregates by recycled aggregates. Fibre replacement at a 100% replacement, and the complete replacement of aggregates and fibres, however, reduced the flexural strength, especially the post-cracking behaviour.
- The replacement of natural aggregates by recycled aggregates did not affect significantly to the durability properties.

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