

Review

# Effect of Design Parameters on Compressive and Split Tensile Strength of Self-Compacting Concrete with Recycled Aggregate: An Overview

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**Abstract:** One of the prime objectives of this review is to understand the role of design parameters on the mechanical properties (Compressive and split tensile strength) of Self-Compacting Concrete (SCC) with recycled aggregates (Recycled Coarse Aggregates (RCA) and Recycled Fine Aggregates (RFA)). The design parameters considered for review are Water to Cement (W/C) ratio, Water to Binder (W/B) ratio, Total Aggregates to Cement (TA/C) ratio, Fine Aggregate to Coarse Aggregate (FA/CA) ratio, Water to Solid (W/S) ratio in percentage, superplasticizer (SP) content (kg/cu.m), replacement percentage of RCA, and replacement percentage of RFA. It is observed that with respect to different grades of SCC, designed parameters affect the mechanical properties of SCC with recycled aggregates.

**Keywords:** self-compacting concrete; recycled aggregates; design parameters; mechanical properties



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## 1. Introduction

One of the most widely used products in the world today are aggregates, specifically sand and gravel, which are used in the construction of buildings in the preparation of concrete or other types of mixtures. In fact, after water, concrete is the most consumed product on the planet and is directly related to the level of development of countries. This material is used not only for the construction of new civil/architectural works but also for the repair, rehabilitation, and/or reconstruction of existing works. Therefore, there is evidence of an increase in the generation of concrete waste related to the construction process and demolition activities (concrete, brick, masonry, tiles, and ceramic materials) that are related to population growth and the modernization of regions [1,2]. The development of civil work generates a large amount of waste that can be reused. In the first case, the best scenario would be reusing the waste as fillers for the development of new civil works and, in the second case, they are disposed of in municipal landfills, which results in competing for space with municipal solid waste when managed in the same facilities [3] or inadequately abandoned, generating an environmental impact due to the loss of landscape quality in the different localities and environmental pollution [4,5]. This is without taking into consideration the significant volume of debris generated annually as a consequence of natural disasters and wars, which additionally increases the costs of waste and debris management [6,7]. For example, the waste management costs of Hurricane Katrina exceeded \$4 billion [8].

In terms of numbers, it can be noted that: (1) For the year 2010, 36% of waste worldwide corresponded to construction and demolition [8,9]; (2) the global average generation of special construction and demolition waste worldwide corresponds to 1.68 kg/capita/day

in 2018. Based on this reality, researchers and specialists from universities and research and quality control centers around the world have focused on providing management solutions. Likewise, several countries have, at the legislative level, adopted the promotion and provided incentives to reuse waste; which has been reflected in the statistics. The amount of waste recovered in the EU has been increasing; it has increased from 45.4% in 2014 to 53.2% in 2018. In the EU, 37.8% of the waste generated in 2018 was recycled, 9.9% used as landfill, and 5.6% used for energy recovery. The remaining 46.8% was landfilled (38.8%) and incinerated without energy recovery (1.0%) or otherwise disposed of (7%). In this context, the European 2020 Strategy establishes the following objectives for waste policy in all member states: (a) reduction in waste generated; (b) increase in recycling and reuse; (c) limitation of incineration; (d) limitation of the use of landfills [10,11]. With these premises, the need for waste management policies that reduce environmental and health impacts and improve the efficiency of available resources is clear. The long-term goal is to turn the world into a recycling society by avoiding waste and using waste as a resource wherever possible. The aim is to achieve much higher levels of recycling and minimize the extraction of additional natural resources.

Currently, there are numerous studies that support the use of construction and the demolition of waste in the production of recycled concrete [12–30] and recycled mortars [31–49]. However, despite the upward trend in the reuse of demolition waste, it has been shown that the use of recycled aggregate materials can limit or decrease the properties of concrete (strength, durability, and service capacity) due to old bonded mortar, irregular shapes, and increased porosity. In other words, there is a direct dependence between the properties of concrete and the degree of substitution used with recycled aggregates [50–52]. Several tests have concluded that the incorporation of recycled products (coarse aggregates) should not exceed 20% to preserve the properties of recycled concrete; this is a worldwide normative recommendation. In the case of fine material, although it is not regulated or is not allowed, scientific studies have shown that there is no alteration when it does not exceed 10% substitution and it can be improved with granulometric gradation in the addition of fine material generating greater cohesiveness [38,52–59].

Concrete is definitely one of the most versatile materials used in construction, as evidenced by the increase in its production in recent decades. It has great durability and strength, both of which are properties obtained by compaction. An alternative product is a self-compacting concrete (SSC), a two-phase material with improved properties that possess good fluidity and filling capacity around complex formwork and reinforcement. It can be cast into the formwork and consolidated by the application of weight without the need for external vibrations to achieve compaction. SSC is used to facilitate proper filling and structural performance of restrained and/or reinforced areas [60,61]. This material possesses different characteristics from traditional concrete, for example, in terms of strength. The idea of this material was first introduced in 1992 by Okamura and has gained ground over time in the construction industry [60,62,63] due to the ease of placement in hard-to-reach areas with less effort and in less time [64]. Research and development in the construction industry have focused on evaluating techniques to improve the properties of self-compacted concrete, achieving higher performance in hardening, strength, durability, and surface quality [64–66]. The advantages of this type of material include technological, social, and economic advantages; however, its cost is two to three times higher than that of conventional concrete due to the high demand for cementations materials and chemical admixtures (superplasticizers or water reducers). In this sense, various mineral admixtures have been used, such as limestone, fly ash, and ground brick residues, to reduce costs and increase the slump of the concrete mix with the aim of improving mechanical properties. In this case, the deformability and cohesion, its durability, and the packing of the particles to obtain a decrease in permeability thus highlights the importance of making a proper selection of the aggregates to be used [67–70].

In view of the concrete industry's high energy consumption due to the high demand for natural resources and the environmental risks it poses, recycled aggregates have been

used as partial or full substitutes to minimize the environmental impact, taking a significant step towards establishing a sustainable society and boosting the circular economy [51,71,72]. Recycled aggregate is a type of composite material, the quality of which depends directly on the origin of the waste, the place and reason for demolition, and the original characteristics of the concrete [72]. Therefore, we should not lose sight of the fact that any change in the aggregate, no matter how small it may seem, will have a significant effect not only on the properties of the concrete but also on the cost of production, transportation, and commercialization. In this sense, several researchers have focused their studies on the use of recycled aggregates both coarse, in most cases, and fine [53,59,73–75]. The coarse recycled aggregate consists of two different materials: natural coarse aggregate and cement mortar bonded to the coarse aggregate (between 20–70%) [17]. Majeed Khan et al. (2015) [67] observed that the fresh properties of self-compacting concrete with recycled aggregates could be maintained within EFNARC standards, although the compressive strength was found to be slightly lower than that of self-compacting concrete with normal aggregates.

Regarding the relationship between the mechanical properties of concrete (compressive and flexural strength) obtained with recycled aggregates, some studies have been carried out using different substitution percentages and finding, for example, that the use of variable amounts of aggregates between 10–40% by weight (waste from a 25-year-old building) generates a decrease in properties, with the most favorable value being 30% by weight substitution [76]. Likewise, it is indicated that, with up to 40% by weight substitution of recycled fine and coarse aggregate, a structural self-compacted concrete is obtained without significant differences compared to conventional concrete [77]. Compressive strength, tensile strength, flexural strength, and elasticity have developed well even with 100% substitution as a consequence of the improved microstructure. On the other hand, the hardening, stiffness, and flexural toughness properties may decrease with the incorporation of aggregates, although a compressive strength of 39 MPa can be obtained with 100% substitution inclusive [78]. Additionally, self-compacting concrete usually possesses higher water absorption than normal concrete due to the lower specific gravity of the old mortar that is bound to the original concrete. Moreover, the density of SCC with aggregates is lower than that of conventional concrete due to its high porosity [76].

Due to the need to optimize the management of solid waste associated with construction activities and the demand for materials that, in addition to being more sustainable, have adequate mechanical properties that guarantee high durability, research has been carried out on the mechanical properties (for example, compressive and tensile strength) of self-compacting concrete obtained conventionally or with the use of recycled aggregates by using different raw materials, design parameters, and verification tests; therefore, it is necessary to carry out an updated general review that allows the compilation of the advances achieved so far in this area of knowledge that will serve as a substantial contribution for the establishment of criteria and, at the time, of implementation in the civil works with respect to the establishment or adaptation of the existing regulations.

### *Research Significance*

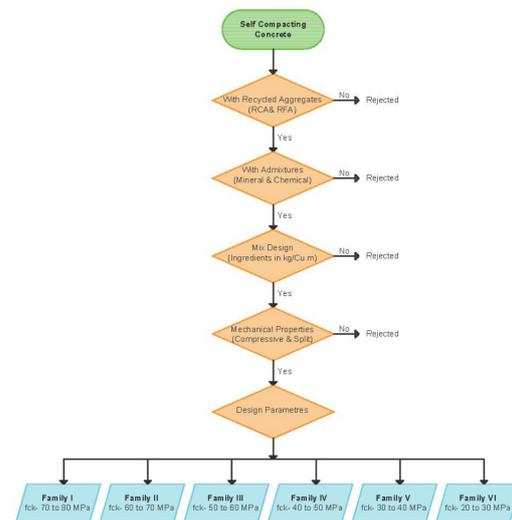
It is important to understand the role of design parameters on the mechanical properties of SCC. This review plays a vital role for upcoming researchers or engineers to understand the requirement of design parameters for SCC, while including recycled aggregates. Several countries across the globe are nowadays standardizing the properties of recycled aggregates for usage in concrete.

## **2. Review Methodology**

### *2.1. Search Strategies*

The review methodology used in this study is shown in Figure 1. Articles with respect to SCC are searched and all other articles are neglected. In order to perform deep analysis, SCC articles with recycled aggregate are given more priority and the remaining articles are omitted. Additives are used not only to reduce the cost of the mixture, but also to improve

the properties of the SCC mixture needed in the system. Hence, the articles with admixtures are given more importance. In order to derive the design parameters, it is essential that there is mixed design in the literature (weight of ingredients per cubic meter), compressive strength, and split tensile strength.



**Figure 1.** Review methodology.

## 2.2. Data Extraction

Design parameters are calculated from the available mix design in the literature. The various ingredients weight in terms of  $\text{kg}/\text{m}^3$  required for SCC to satisfy the fresh and hardened concrete properties is called mix design. Design parameters considered for this review are W/C ratio, W/B ratio, TA/C ratio, FA/CA ratio, SP, W/S ratio (%), % of RFA, and % of RCA. With respect to available ingredients in mixed design from the literature, the design parameters are estimated. Binder content includes the mineral admixtures that possess binding properties, which are used in the mix. The sum of fine aggregate, coarse aggregate, and recycled aggregates is known as total aggregates. Solid contents such as cement, binder, and aggregates are added to give total solid content in the mix. For W/S ratio, the water includes all liquid content in the mix. The articles without mix proportions or without any one of the ingredients are omitted from the review process.

From the available literature, the results are grouped into six families based on the compressive strength grade. Twenty-eight days compressive strength of control or reference SCC mix is used to classify the proportions irrespective of the size of the specimen, shape of the specimen, and various international standards or codes used for testing of the specimen. For example, Family I consist of data based on the reference or control 28 days compressive strength lies in the range of 70 MPa to 80 MPa. In a similar fashion, family II, family III, family IV, family V, and family VI consists of 28 days compressive strength that lies in the range of 60 MPa to 70 MPa, 50 MPa to 60 MPa, 40 MPa to 50 MPa, 30 MPa to 40 MPa, and 20 MPa to 30 MPa, respectively. Corresponding split tensile strength at 28 days is also tabulated irrespective of nature of size, the shape of the specimen, and international standards or codes. If one of the compressive strengths is not available for evaluation in the article, then that corresponding article itself is neglected for review purpose.

## 3. Design Parameters from Literature

Three articles are found in the literature with 28 days compressive strength in the range of 70 MPa to 80 MPa and they are named Family I and are tabulated in Table 1. One of the articles consists of nine different mix proportions as shown in Table 1. It is found that, for higher strength, there is a lower W/C or W/B ratio observed from Table 1. TA/C ratio lies in the range of 3.3 to 5.2 for high strength mix. FA/CA ratio lies in the range of 1.7 to 2.5 and SP available in the mix falls in the range of 2 kg to 7 kg.

**Table 1.** Design Parameters for Family I (Compressive strength range: 70 MPa to 80 MPa) according to the literature.

Authors	Design Parameters								Strength (MPa)	
	W/C	W/B	TA/C	FA/CA	SP (kg)	W/S (%)	% RFA	% RCA	fc	fs
Gesoglu et al., 2015 (A) [79]	0.30	0.23	3.800	1.789	6.29	5.85	-	0	77.96	4.25
	0.30	0.23	3.540	1.789	4.95	6.16	-	100	68.67	3.50
Gesoglu et al., 2015 (B) [79]	0.30	0.20	4.340	2.044	7.00	5.11	-	0	81.40	4.46
	0.30	0.20	4.050	2.044	6.26	5.37	-	100	70.39	4.13
Gesoglu et al., 2015 (D) [79]	0.43	0.28	5.223	2.459	4.55	6.36	-	0	72.47	3.75
	0.43	0.28	4.867	2.459	4.09	6.72	-	100	63.89	3.24
Gesoglu et al., 2015 (E) [79]	0.30	0.23	3.800	1.789	6.29	5.85	0	-	77.96	4.25
	0.30	0.23	3.571	1.789	4.51	6.12	100	-	61.97	3.15
Gesoglu et al., 2015 (F) [79]	0.30	0.20	4.340	2.044	7.00	5.11	0	-	81.40	4.46
	0.30	0.20	4.081	2.044	4.20	5.34	100	-	64.61	3.59
Gesoglu et al., 2015 (H) [79]	0.43	0.28	5.223	2.459	4.55	6.36	0	-	72.47	3.75
	0.43	0.28	4.908	2.459	2.70	6.67	100	-	61.04	2.81
Gesoglu et al., 2015 (I) [79]	0.30	0.23	3.800	1.789	6.29	5.85	0	0	77.96	4.25
	0.30	0.23	3.313	1.789	3.44	6.46	100	100	55.76	2.72
Gesoglu et al., 2015 (J) [79]	0.30	0.20	4.340	2.044	7.00	5.11	0	0	81.40	4.46
	0.30	0.20	3.785	2.044	3.79	5.64	100	100	57.41	3.16
Gesoglu et al., 2015 (L) [79]	0.43	0.28	5.223	2.459	4.55	6.36	0	0	72.47	3.75
	0.43	0.28	4.552	2.459	2.62	7.06	100	100	52.92	2.59
Wang et al., 2020 [80]	0.36	0.35	4.366	2.309	6.50	6.64	0	-	72.30	4.43
	0.36	0.35	4.232	2.174	6.50	6.81	5	-	58.50	4.15
	0.36	0.35	4.269	2.174	6.50	6.77	10	-	56.00	4.70
	0.36	0.35	4.202	2.174	6.50	6.85	15	-	50.10	3.67
	0.36	0.35	4.067	2.174	6.50	7.03	25	-	32.20	3.30
	0.41	0.34	3.840	2.180	7.00	8.44	0	0	74.10	3.60
Sadeghi-Nik. et al., 2019 (B) [81]	0.41	0.34	3.840	2.180	7.00	8.44	20	20	55.00	3.10
	0.41	0.34	3.840	2.180	7.00	8.44	40	40	52.10	2.90
	0.41	0.34	3.840	2.180	7.00	8.44	60	60	51.00	2.70
	0.41	0.34	3.840	2.180	7.00	8.44	80	80	50.50	2.70
	0.41	0.34	3.840	2.180	7.00	8.44	100	100	40.00	2.50

W/C = water to cement ratio; W/B = water to binder ratio; SCC = self-compacting concrete; RCA = recycled coarse aggregate; RFA = recycled fine aggregate; SP = superplasticizer; TA/C = total aggregate to cement ratio; FA/CA = fine aggregate to coarse aggregate Ratio; W/S = water to solid percentage; fc = Compressive strength; fs = split tensile strength.

Compressive strength at 28 days for the control or reference SCC in the range of 60 MPa to 70 MPa is observed in four articles in the literature and they are named Family II. The design parameters and strength values are tabulated in Table 2. Predominant literature shows that there is an increase in W/C ratio and W/B ratio when compared to Table 1 with respect to compressive strength. An increase in TA/C ratio and FA/CA ratio is observed by comparing Tables 1 and 2. A decrease in usage of SP and W/S ratio in percentage is observed for Family II when compared to Family I.

**Table 2.** Design Parameters for Family II (Compressive strength range: 60 MPa to 70 MPa) according to the literature.

Authors	Design Parameters								Strength (MPa)	
	W/C	W/B	TA/C	FA/CA	SP (kg)	W/S (%)	% RFA	% RCA	fc	fs
Gesoglu et al., 2015 (C) [79]	0.430	0.32	4.563	2.148	3.11	7.29	-	0	66.63	3.50
	0.430	0.32	4.252	2.148	2.55	7.70	-	100	55.38	2.89
Gesoglu et al., 2015 (G) [79]	0.430	0.32	4.563	2.148	3.11	7.29	0	-	66.63	3.50
	0.430	0.32	4.288	2.148	1.82	7.65	100	-	48.69	2.53
Gesoglu et al., 2015 (K) [79]	0.430	0.32	4.563	2.148	3.11	7.29	0	0	66.63	3.50
	0.430	0.32	3.978	2.148	1.78	8.10	100	100	46.04	2.20
Revilla Cuesta et al., 2020 [82]	0.459	0.29	5.583	3.833	6.60	6.39	-	0	60.00	3.20
	0.470	0.29	5.516	3.767	6.60	6.60	-	25	56.00	3.03
	0.482	0.30	5.433	3.683	6.60	6.85	-	50	44.00	2.75
	0.506	0.32	5.367	3.617	6.60	7.26	-	75	31.00	2.50
	0.530	0.33	5.283	3.533	6.60	7.70	-	100	30.00	2.40
	0.310	0.17	5.625	2.031	1.80	4.13	-	0	63.36	5.30
Fiol et al., 2018 (C) [83]	0.300	0.16	5.688	2.031	1.80	3.97	-	20	64.13	5.21
	0.270	0.14	5.469	2.094	2.25	3.68	-	50	66.82	4.95
	0.250	0.13	5.500	2.250	2.85	3.39	-	100	72.81	5.00
Behera et al., 2019 (A) [84]	0.560	0.34	5.350	2.960	5.23	7.98	0	-	60.76	4.13
	0.560	0.34	5.350	2.960	5.23	7.98	50	-	55.76	3.82
	0.560	0.34	5.350	2.960	5.23	7.98	100	-	44.54	3.20
	0.560	0.34	5.350	2.960	5.23	7.98	0	-	60.76	4.13
Behera et al., 2019 (B) [84]	0.560	0.34	5.350	2.960	3.15	7.98	0	-	44.54	3.56
	0.560	0.34	5.350	2.960	4.20	7.98	100	-	38.41	2.71

W/C = water to cement ratio; W/B = water to binder ratio; SCC = self-compacting concrete; RCA = recycled coarse aggregate; RFA = recycled fine aggregate; SP = superplasticizer; TA/C = total aggregate to cement ratio; FA/CA = fine aggregate to coarse aggregate Ratio; W/S = water to solid percentage; fc = Compressive strength; fs = split tensile strength.

Family III consists of compressive strength at 28 days for control SCC in the range of 50 MPa to 60 MPa and the design parameters are tabulated in Table 3. Ten articles with control SCC compressive strength in the range of 50 MPa to 60 MPa along with split tensile strength in the range of 0.96 MPa to 5.50 are tabulated in Table 3. Aslani et al., 2018 [85]

reports that higher the TA/C ratio results in a higher W/C ratio which results in a higher W/S ratio in percentage. Aslani et al., 2018 [85] also used the larger proportion of binder material in a mix that resulted in a decrease in SP content and W/B ratio. Apart from Aslani et al., 2018 [85], there is some relationship that exhibits between design parameters and strength. An increase in W/S ratio when compared to Family I and II is observed due to increase in quantity of available liquid in the system.

**Table 3.** Design Parameters for Family III (Compressive strength range: 50 MPa to 60 MPa) according to the literature.

Authors	Design Parameters							Strength (MPa)		
	W/C	W/B	TA/C	FA/CA	SP (kg)	W/S (%)	% RFA	% RCA	fc	fs
Señas et al., 2016 (B) [86]	0.40	0.40	4.373	2.566	4.15	7.44	0	0	51.20	4.60
	0.40	0.40	4.272	2.566	4.98	7.59	0	50	48.10	4.10
	0.40	0.40	4.229	2.523	5.81	7.65	50	50	45.60	3.80
	1.13	0.45	9.311	5.090	3.75	9.57	0	0	50.39	3.70
Aslani et al., 2018 (C) [85]	1.13	0.45	9.225	5.050	2.95	9.64	10	20	47.74	4.38
	1.13	0.45	9.139	5.010	3.55	9.71	20	20	46.06	3.98
	1.13	0.45	9.054	4.960	3.75	9.78	30	20	45.13	3.79
	1.13	0.45	8.968	4.920	3.95	9.85	40	20	43.82	3.80
	0.35	0.35	3.177	1.510	4.02	8.38	-	0	53.45	4.39
	0.35	0.35	3.143	1.510	4.16	8.45	-	50	46.54	3.49
	0.35	0.35	3.110	1.510	4.72	8.52	-	100	43.89	3.32
	0.35	0.18	6.219	3.019	4.78	4.26	-	100	21.00	1.57
Guo et al., 2020 [87]	0.35	0.18	6.219	3.019	5.67	4.26	-	100	38.38	2.75
	0.35	0.18	6.219	3.019	6.86	4.26	-	100	49.44	3.66
	0.35	0.09	12.438	6.038	7.40	2.13	-	100	13.64	0.96
	0.35	0.09	12.438	6.038	7.28	2.13	-	100	30.84	1.67
	0.35	0.09	12.438	6.038	7.57	2.13	-	100	42.75	2.89
	0.31	0.15	6.207	2.241	1.80	3.76	-	0	58.30	5.50
	0.32	0.16	6.276	2.241	1.80	3.85	-	20	60.25	5.15
	0.27	0.13	6.034	2.310	2.25	3.35	-	50	58.52	5.20
Fiol et al., 2018 (B) [83]	0.25	0.12	6.069	2.483	2.85	3.09	-	100	70.56	5.32
	0.31	0.24	4.874	2.057	10.80	5.03	-	0	57.00	3.50
	0.31	0.24	4.920	2.057	10.80	5.00	-	100	54.00	3.70
	0.34	0.26	4.777	2.017	9.50	5.61	-	0	56.60	3.20
	0.34	0.26	4.823	2.017	9.50	5.57	-	100	53.20	3.40
	0.37	0.29	4.683	1.977	8.10	6.20	-	0	56.10	3.00
	0.37	0.29	4.729	1.977	8.10	6.15	-	100	52.50	3.10
	0.40	0.31	4.586	1.937	6.80	6.81	-	0	55.60	2.80
Uygunoglu et al., 2014 [88]	0.40	0.31	4.631	1.937	6.80	6.76	-	100	51.70	2.80
	0.44	0.25	4.447	1.947	8.50	7.05	0	-	53.70	2.90
	0.44	0.25	4.447	1.888	8.50	7.05	25	-	64.30	3.20
	0.44	0.25	4.447	1.829	8.50	7.05	50	-	62.30	3.40
	0.44	0.25	4.447	1.771	8.50	7.05	75	-	56.30	3.30
	0.44	0.25	4.447	1.709	8.50	7.05	100	-	53.20	3.50
	0.41	0.34	3.843	2.176	7.00	8.10	0	0	52.00	3.30
	0.41	0.34	3.843	2.176	7.00	8.10	20	20	43.10	2.70
Sadeghi-Nik., et al., 2019 (B) [81]	0.41	0.34	3.843	2.176	7.00	8.10	40	40	41.00	2.50
	0.41	0.34	3.843	2.176	7.00	8.10	60	60	40.10	2.50
	0.41	0.34	3.843	2.176	7.00	8.10	80	80	38.10	2.20
	0.41	0.34	3.843	2.176	7.00	8.10	100	100	30.00	2.10
	0.42	0.25	3.748	2.098	4.00	7.80	-	0	50.00	7.20
	0.43	0.27	3.748	2.098	4.00	7.99	-	50	48.00	7.10
	0.45	0.28	3.748	2.098	4.00	8.36	-	100	46.00	6.20
	0.49	0.35	3.315	1.831	4.50	10.36	-	0	59.00	4.10
Tang et al., 2016 [91]	0.49	0.35	3.285	1.831	4.50	10.43	-	25	64.00	4.90
	0.49	0.35	3.258	1.831	4.50	10.49	-	50	65.00	4.10
	0.49	0.35	3.231	1.831	4.50	10.55	-	75	60.00	3.90
	0.49	0.35	3.202	1.831	4.50	10.61	-	100	54.00	3.80
	0.43	0.32	4.708	2.365	4.90	6.47	-	0	52.30	4.86
Tuyan et al., 2014 (A) [74]	0.43	0.32	4.708	2.365	5.50	6.47	-	20	54.70	4.69
	0.43	0.32	4.708	2.365	5.70	6.47	-	40	57.20	4.51
	0.43	0.32	4.708	2.365	6.20	6.47	-	60	51.10	4.33

W/C = water to cement ratio; W/B = water to binder ratio; SCC = self-compacting concrete; RCA = recycled coarse aggregate; RFA = recycled fine aggregate; SP = superplasticizer; TA/C = total aggregate to cement ratio; FA/CA = fine aggregate to coarse aggregate Ratio; W/S = water to solid percentage; fc = Compressive strength; fs = split tensile strength.

Family IV consists of control mix compressive strength at 28 days in the range of 40 MPa to 50 MPa and their corresponding split tensile strength along with design parameters are tabulated in Table 4. When compared to Family I, Family II, and Family III, there is an increase in W/C and W/B ratio observed. With the exception of Kou and Poon, 2009 [89], there is a decrease in usage of SP when compared to Family I, II, and III. An increase in W/C or W/C ratio counteracts with a decrease in usage of SP. Increase in W/S when compared to other previous families is due to the availability of larger amounts of water in the system, which results in a decrease in strength.

**Table 4.** Design Parameters for Family IV (Compressive strength range: 40 MPa to 50 MPa) according to the literature.

Authors	Design Parameters							Strength (MPa)		
	W/C	W/B	TA/C	FA/CA	SP (kg)	W/S (%)	% RFA	% RCA	fc	fs
Señas et al., 2016 (A) [86]	0.40	0.40	4.373	2.566	2.91	7.44	-	-	47.60	4.40
	0.40	0.40	4.272	2.566	5.40	7.59	-	50	46.60	4.30
	0.40	0.40	4.229	2.523	6.23	7.65	50	50	47.00	3.90
	0.47	0.41	4.010	2.260	3.20	9.12	-	0	46.36	4.60
Martínez-García et al., 2020 [92]	0.47	0.41	4.010	2.260	4.00	9.12	-	25	55.58	4.10
	0.47	0.41	4.010	2.260	4.80	9.12	-	50	54.70	3.20
	0.47	0.41	4.010	2.260	5.40	9.12	-	100	44.04	3.30
	0.40	0.18	7.200	2.600	1.80	4.22	-	0	49.09	5.17
Fiol et al., 2018 (A) [83]	0.39	0.17	7.280	2.600	1.80	4.08	-	20	49.98	5.06
	0.35	0.15	7.000	2.680	2.25	3.77	-	50	55.64	4.85
	0.32	0.14	7.040	2.880	2.85	3.43	-	100	56.75	4.92
	0.40	0.28	3.345	1.533	1.53	8.38	-	0	42.91	4.45
Duan et al., 2020 (A) [71]	0.40	0.28	3.345	1.533	1.53	8.38	-	0	42.41	4.44
	0.40	0.28	3.345	1.533	1.53	8.38	-	25	40.45	3.64
	0.40	0.28	3.345	1.533	1.53	8.38	-	50	36.93	3.60
	0.40	0.28	3.345	1.533	1.53	8.38	-	100	34.85	3.20
Duan et al., 2020 (B) [71]	0.40	0.28	3.345	1.533	1.53	8.38	-	0	42.91	4.45
	0.40	0.28	3.345	1.533	1.53	8.38	-	0	41.25	3.89
	0.40	0.28	3.345	1.533	1.53	8.38	-	25	40.73	3.63
	0.40	0.28	3.345	1.533	1.53	8.38	-	50	35.97	3.34
Pan et al., 2019 [93]	0.40	0.28	3.345	1.533	1.53	8.38	-	100	34.43	2.89
	0.41	0.33	3.904	1.812	1.16	7.96	-	30	45.60	3.10
	0.46	0.33	4.331	2.010	1.16	8.04	-	30	49.00	3.30
	0.52	0.33	4.877	2.264	1.16	8.07	-	30	42.53	2.60
Kou and Poon., 2009 [89]	0.59	0.33	5.581	2.591	1.16	8.01	-	30	37.22	2.30
	0.70	0.33	6.573	3.051	1.16	8.07	-	30	32.11	2.00
	0.83	0.33	7.808	3.624	1.16	8.05	-	30	28.10	1.80
	0.44	0.25	4.447	1.947	8.50	7.05	0	-	44.30	2.90
Manzi et al., 2017 [77]	0.44	0.25	4.447	1.888	8.50	7.05	25	-	44.50	2.70
	0.44	0.25	4.447	1.829	8.50	7.05	50	-	43.40	2.70
	0.44	0.25	4.447	1.771	8.50	7.05	75	-	41.30	2.60
	0.44	0.25	4.447	1.709	8.50	7.05	100	-	38.70	2.50
Nili et al., 2019 (A) [94]	0.51	0.31	4.566	1.660	4.90	8.23	0	0	43.80	3.30
	0.49	0.30	4.451	2.560	5.25	8.06	12	13	45.40	3.20
	0.49	0.30	4.389	2.426	5.25	8.14	19	21	50.30	2.50
	0.51	0.31	4.469	2.786	5.60	8.36	0	40	51.10	3.10
Nili et al., 2019 (B) [94]	0.44	0.31	3.605	2.804	3.34	8.79	0	0	46.30	3.40
	0.44	0.31	3.567	2.775	3.89	8.86	0	100	32.10	3.40
	0.44	0.31	3.569	2.775	3.89	8.86	50	0	35.20	3.20
	0.44	0.32	3.531	2.746	3.89	8.94	50	100	38.20	3.40
Tuyan et al., 2014 (B) [74]	0.44	0.31	3.605	2.804	3.34	8.79	0	0	46.30	3.40
	0.48	0.32	3.914	3.044	3.47	8.83	0	0	46.40	4.30
	0.48	0.32	3.873	3.013	3.85	8.91	0	100	52.90	4.10
	0.48	0.32	3.875	3.013	4.24	8.90	50	0	32.50	2.90
Singh et al., 2019 (A) [2]	0.48	0.32	3.834	2.982	4.62	8.98	50	100	31.80	3.10
	0.48	0.36	4.549	2.263	3.30	7.41	-	0	42.20	4.33
	0.48	0.36	4.549	2.263	3.40	7.41	-	20	44.00	4.44
	0.48	0.36	4.549	2.263	3.50	7.41	-	40	44.30	4.01
Singh et al., 2019 (B) [2]	0.48	0.36	4.549	2.263	3.70	7.41	-	60	40.90	3.85
	0.57	0.40	3.488	1.884	1.23	11.63	-	0	42.34	2.62
	0.57	0.40	3.488	1.884	1.23	11.63	-	50	36.49	2.49
	0.57	0.40	3.488	1.884	1.23	11.63	-	100	31.53	2.37
Singh et al., 2019 (C) [2]	0.57	0.40	3.488	1.884	1.23	11.63	-	0	42.34	2.62
	0.57	0.40	3.488	1.884	1.23	11.63	-	50	39.42	2.55
	0.57	0.40	3.488	1.884	1.23	11.63	-	100	35.08	2.46
	0.57	0.40	3.488	1.884	1.23	11.63	-	0	42.34	2.62
Singh et al., 2019 (D) [2]	0.57	0.40	3.488	1.884	1.23	11.63	-	50	38.69	2.54
	0.57	0.40	3.488	1.884	1.23	11.63	-	100	33.88	2.42
	0.57	0.40	3.488	1.884	1.23	11.63	-	0	42.34	2.62
	0.57	0.40	3.488	1.884	1.23	11.63	-	50	41.85	2.61
	0.57	0.40	3.488	1.884	1.23	11.63	-	100	38.02	2.52

W/C = water to cement ratio; W/B = water to binder ratio; SCC = self-compacting concrete; RCA = recycled coarse aggregate; RFA = recycled fine aggregate; SP = superplasticizer; TA/C = total aggregate to cement ratio; FA/CA = fine aggregate to coarse aggregate Ratio; W/S = water to solid percentage; fc = Compressive strength; fs = split tensile strength.

For Family V, the control SCC compressive strength at 28 days lies in the range of 30 MPa to 40 MPa and their corresponding split tensile strengths at 28 days are tabulated in Table 5. Apart from Aslani et al., 2018 [85] and Babaloo et al., 2020 [95], there is no such drastic increase in W/C or W/B ratio when compared to the other literature in Family V. However, when compared to family IV there is an increase in W/C and W/B ratio. Bahrami et al., 2020b [62], Sun et al. [96], 2020, and Surendar et al., 2021 [97] used a constant TA/C ratio, FA/CA ratio, and W/S ratio in percentage and reported that there was a slight variation in the strength requirement for minimum modification in aggregates. Several authors tried with 100% replacement for the natural aggregate and achieved the minimum requirement of strength.

**Table 5.** Design Parameters for Family V (Compressive strength range: 30 MPa to 40 MPa) according to the literature.

Authors	Design Parameters								Strength (MPa)	
	W/C	W/B	TA/C	FA/CA	SP (kg)	W/S (%)	% RFA	% RCA	fc	fs
Aslani et al., 2018 (B) [85]	1.13	0.45	8.399	5.090	4.40	10.37	0	0	38.93	3.54
	1.13	0.45	8.355	5.050	3.95	10.41	10	20	38.36	3.89
	1.13	0.45	8.310	5.010	4.15	10.45	20	20	39.85	3.43
	1.13	0.45	8.266	4.960	4.35	10.50	30	20	37.68	3.27
	1.13	0.45	8.221	4.920	4.55	10.54	40	20	40.68	3.34
Bahrami et al., 2020 (A) [62]	0.41	0.33	4.325	3.000	3.80	7.35	-	-	38.99	3.61
	0.41	0.33	4.325	3.000	3.80	7.35	25	-	36.70	3.45
	0.41	0.33	4.325	3.000	3.80	7.35	50	-	32.80	3.22
	0.41	0.33	4.325	3.000	3.80	7.35	75	-	29.60	2.70
	0.41	0.33	4.325	3.000	3.80	7.35	100	-	24.80	2.50
	0.41	0.33	4.325	3.000	3.80	7.35	-	-	38.99	3.61
	0.41	0.33	4.325	3.000	3.80	7.35	-	25	37.00	3.55
	0.41	0.33	4.325	3.000	3.80	7.35	-	50	33.51	3.38
Bahrami et al., 2020 (B) [62]	0.41	0.33	4.325	3.000	3.80	7.35	-	75	31.36	2.76
	0.41	0.33	4.325	3.000	3.80	7.35	-	100	25.83	2.46
	0.45	0.36	4.188	2.513	2.88	8.28	-	0	35.50	3.05
	0.45	0.36	4.141	2.513	2.88	8.35	-	25	27.69	2.70
Silva et al., 2016 [98]	0.45	0.36	4.095	2.513	2.89	8.42	-	50	29.11	2.71
	0.45	0.36	4.049	2.513	2.89	8.49	-	75	30.18	2.35
	0.45	0.36	4.003	2.513	2.90	8.57	-	100	25.21	2.28
	0.40	0.32	4.027	1.949	2.40	7.58	0	0	40.26	4.03
	0.40	0.32	4.027	1.949	2.42	7.58	10	0	39.05	3.28
Sun et al., 2020 (A) [96]	0.40	0.32	4.027	1.949	2.44	7.58	10	25	38.04	3.32
	0.40	0.32	4.027	1.949	2.46	7.58	10	50	35.46	3.37
	0.40	0.32	4.027	1.949	2.48	7.58	10	100	33.35	3.28
	0.40	0.32	4.027	1.949	2.40	7.58	0	0	40.26	4.03
	0.40	0.32	4.027	1.949	2.62	7.58	10	0	35.36	3.41
Sun et al., 2020 (B) [96]	0.40	0.32	4.027	1.949	2.85	7.58	10	25	35.58	3.53
	0.40	0.32	4.027	1.949	3.28	7.58	10	50	32.63	3.17
	0.40	0.32	4.027	1.949	3.72	7.58	10	100	32.39	2.81
	0.45	0.45	3.429	1.808	1.90	10.16	-	0	36.66	4.12
	0.45	0.45	4.376	1.808	1.90	8.37	-	10	36.22	4.07
Surendar et al., 2021 [97]	0.45	0.45	4.376	1.808	1.90	8.37	-	15	35.77	4.00
	0.45	0.45	4.376	1.808	1.90	8.37	-	20	34.95	3.98
	0.45	0.45	4.376	1.808	1.90	8.37	-	25	34.50	3.96
	0.45	0.45	4.376	1.808	1.90	8.37	-	50	32.44	3.23
	0.45	0.45	4.376	1.808	1.90	8.37	-	75	27.60	2.70
Tuyan et al., 2014 (A) [74]	0.53	0.4	4.867	2.184	2.20	7.83	-	0	37.20	4.19
	0.53	0.4	4.867	2.184	2.40	7.83	-	20	37.70	3.95
	0.53	0.4	4.867	2.184	2.70	7.83	-	40	38.20	3.73
	0.53	0.4	4.867	2.184	3.00	7.83	-	60	35.80	3.52
	0.45	0.45	3.515	1.229	3.46	9.97	-	0	30.60	2.80
Babaloa et al., 2020 (A) [95]	0.81	0.45	11.781	4.813	2.30	5.97	-	100	31.70	3.00
	0.90	0.45	13.09	5.347	2.30	5.97	-	100	33.50	3.20
	1.01	0.45	14.843	6.063	2.29	5.91	-	100	35.80	3.50
	1.15	0.45	16.982	6.937	2.28	5.88	-	100	37.00	3.52
	1.36	0.45	20.053	8.191	2.27	5.89	-	100	39.80	3.70
	1.64	0.45	24.167	9.872	2.26	5.90	-	100	39.20	3.91
	0.45	0.45	3.515	1.229	3.46	9.97	-	0	30.60	2.80
	0.81	0.45	11.781	4.813	2.30	5.97	-	100	31.70	3.00
Babaloa et al., 2020 (B) [95]	0.66	0.37	11.930	4.873	2.82	4.66	-	100	41.40	3.82
	0.81	0.35	13.464	5.500	2.62	5.13	-	100	38.00	3.74
	0.98	0.40	15.202	6.210	2.43	5.55	-	100	37.40	3.68
	1.15	0.45	16.982	6.937	2.28	5.88	-	100	37.00	3.52
	1.34	0.50	19.040	7.778	2.14	6.16	-	100	33.00	3.28
Nieto et al., 2018 (C) [99]	0.45	0.35	4.105	2.328	6.10	8.34	-	0	38.78	2.82
	0.45	0.35	4.093	2.328	6.10	8.36	-	20	43.01	2.63
	0.45	0.35	4.081	2.328	6.10	8.38	-	40	44.96	2.88
	0.45	0.35	4.069	2.328	6.10	8.40	-	60	47.69	3.27
	0.45	0.35	4.105	2.328	6.10	8.34	-	0	38.78	2.82
Nieto et al., 2018 (D) [99]	0.46	0.36	4.093	2.328	6.10	8.59	-	20	40.09	3.33
	0.48	0.37	4.081	2.328	6.10	8.88	-	40	41.30	2.95
	0.49	0.38	4.069	2.328	6.10	9.17	-	60	40.54	2.40
Nieto et al., 2018 (E) [99]	0.45	0.35	4.105	2.328	6.10	8.34	-	0	38.78	2.82
	0.46	0.36	4.093	2.328	6.10	8.59	-	20	40.78	3.34
	0.48	0.37	4.081	2.328	6.10	8.88	-	40	43.07	3.24
	0.49	0.38	4.069	2.328	6.10	9.17	-	60	42.94	3.08

W/C = water to cement ratio; W/B = water to binder ratio; SCC = self-compacting concrete; RCA = recycled coarse aggregate; RFA = recycled fine aggregate; SP = superplasticizer; TA/C = total aggregate to cement ratio; FA/CA = fine aggregate to coarse aggregate Ratio; W/S = water to solid percentage; fc = Compressive strength; fs = split tensile strength.

Family VI consists of control mix compressive strength at 28 days in the range of 20 MPa to 30 MPa and their corresponding split tensile strengths along with the design parameters are tabulated in Table 6. Among all family members, Family VI possesses the highest W/C and W/B ratio, which ultimately results in a higher W/S ratio in percentage.

**Table 6.** Design Parameters for Family VI (Compressive strength range: 20 MPa to 30 MPa) according to the literature.

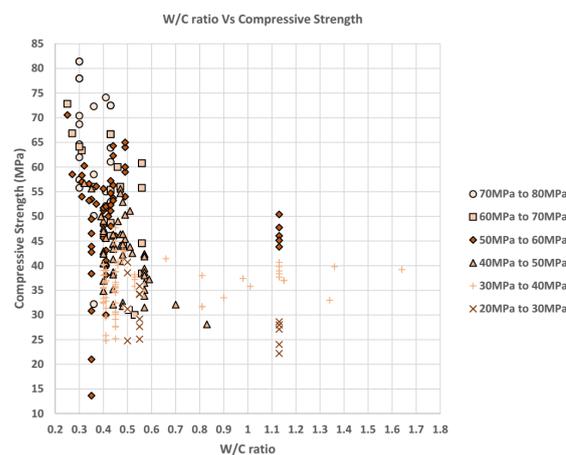
Authors	Design Parameters								Strength (MPa)	
	W/C	W/B	TA/C	FA/CA	SP (kg)	W/S (%)	% RFA	% RCA	fc	fs
Aslani et al., 2018 (A) [85]	1.13	0.45	8.468	5.090	3.35	10.30	0	0	22.21	2.71
	1.13	0.45	8.788	5.050	4.35	10.01	10	20	28.63	3.02
	1.13	0.45	8.743	5.010	4.75	10.05	20	20	28.01	2.75
	1.13	0.45	8.699	4.960	4.95	10.09	30	20	24.03	2.97
	1.13	0.45	8.654	4.920	5.35	10.13	40	20	27.13	3.07
Nieto et al., 2018 (A) [99]	0.55	0.42	4.564	2.589	5.50	9.39	-	0	25.11	2.15
	0.55	0.42	4.550	2.589	5.50	9.41	-	20	27.65	1.61
	0.55	0.42	4.537	2.589	5.50	9.43	-	40	35.86	2.12
	0.55	0.42	4.523	2.589	5.50	9.45	-	60	29.20	2.31
	0.55	0.42	4.510	2.589	5.50	9.47	-	80	34.29	2.10
Nieto et al., 2018 (B) [99]	0.55	0.42	4.496	2.589	5.50	9.50	-	100	34.17	2.52
	0.50	0.38	4.339	2.461	5.80	8.87	-	0	24.78	2.07
	0.50	0.38	4.326	2.461	5.80	8.89	-	20	31.25	2.78
	0.50	0.38	4.313	2.461	5.80	8.91	-	40	40.69	2.74
	0.50	0.38	4.301	2.461	5.80	8.93	-	60	38.56	2.08

W/C = water to cement ratio; W/B = water to binder ratio; SCC = self-compacting concrete; RCA = recycled coarse aggregate; RFA = recycled fine aggregate; SP = superplasticizer; TA/C = total aggregate to cement ratio; FA/CA = fine aggregate to coarse aggregate Ratio; W/S = water to solid percentage; fc = Compressive strength; fs = split tensile strength.

#### 4. Effect of Design Parameters on Strength

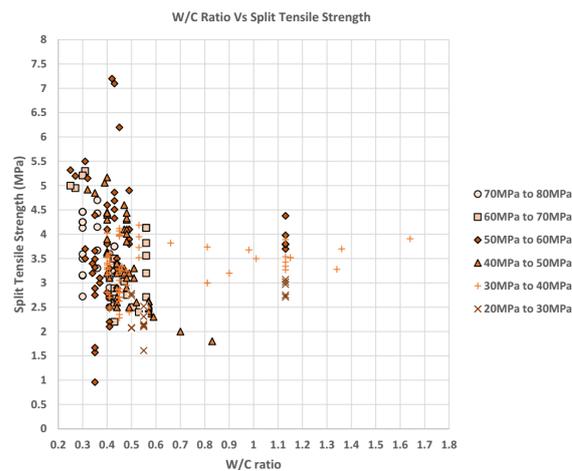
##### 4.1. Effect of W/C Ratio on Compressive Strength and Split Tensile Strength

An increase in the W/C ratio results in a decrease in compressive strength, which is observed in Figure 2. In the vast majority of cases, it is observed that with an increase in W/C ratio, there is a decrease in strength of concrete and lower W/C ratio results in higher strength of SCC. The most predominant W/C ratio for all grades of concrete is observed in the range from 0.30 to 0.60. Higher-strength in concrete is observed with a lower W/C ratio in the range from 0.20 to 0.50.



**Figure 2.** Effect of W/C ratio on various compressive strengths of SCC concrete with recycled aggregate according to the literature.

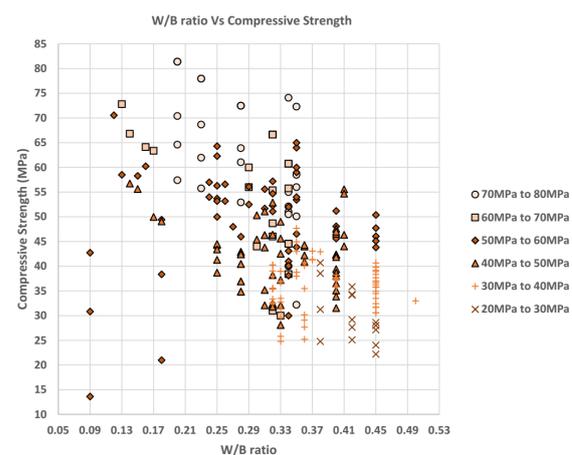
Different grades of concrete exhibit the split tensile strengths mostly in the range from 2.0 MPa to 5.0 MPa in Figure 3. An increase in the W/C ratio results in the decrease in split tensile strength. Most of the split tensile strength from literature possesses a W/C ratio that lies in the range from 0.30 to 0.60. Higher split tensile strength with a range of above 5.0 MPa has a lower W/C ratio in the range from 0.20 to 0.50 and is observed in Figure 3.



**Figure 3.** Effect of W/C ratio on various split tensile strength of SCC concrete with recycled aggregate according to the literature.

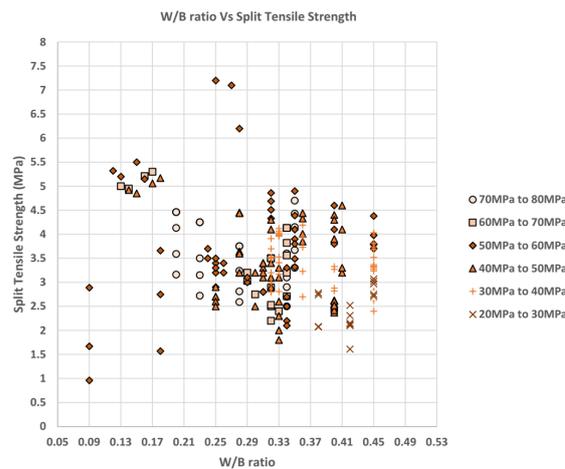
**4.2. Effect of W/B Ratio on Compressive Strength and Split Tensile Strength**

There is a need for mineral admixture in the mix not only for the reduction in the cost of the mix but also to increase the efficiency of the mix. Hence, in the literature, there are different types of mineral admixtures that are added to increase the fresh and hardened property efficiencies of SCC with recycled aggregates. Ingredients that contribute to increasing the binding capacity of concrete are known as binders. In the literature, there are different types of admixtures or binders that are added to the SCC mix in order to counteract the negative impact caused by a recycled aggregate or to improve the specific requirement of SCC itself. Similar to the W/C ratio, the lower the W/B ratio the higher the compressive strength is observed for SCC from Figure 4. The higher W/B ratio lowers in compressive strength because it will reduce the formation of the increased amounts of hydration products which is required for the enhancement of compressive strength. Furthermore, an increase in binder content results in rendering the binder content as filler material rather than a reactive ingredient in the mixture.



**Figure 4.** Effect of the W/B ratio on various compressive strengths of SCC concrete with recycled aggregate according to the literature.

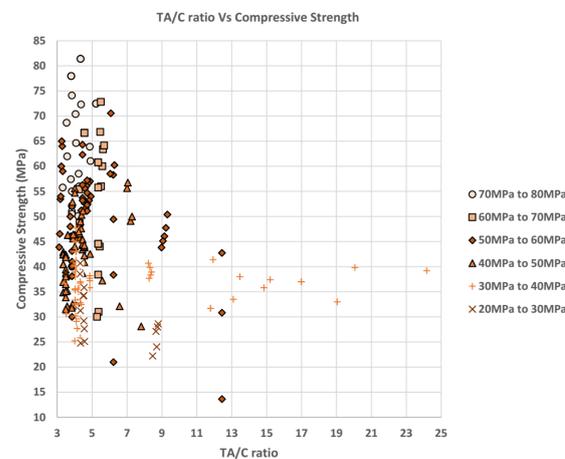
From Figure 5, it is observed that an increase in the W/B ratio results in a drop in split tensile strength and it is also observed that the range of split tensile strength is from 2.0 MPa to 4.5 MPa for the W/Br ratio of 0.25 to 0.45. For the lower compressive strength grade of concrete, the split tensile strength is observed to be less when the W/B ratio is higher.



**Figure 5.** Effect of the W/B ratio on various split tensile strength of SCC concrete with recycled aggregate according to the literature.

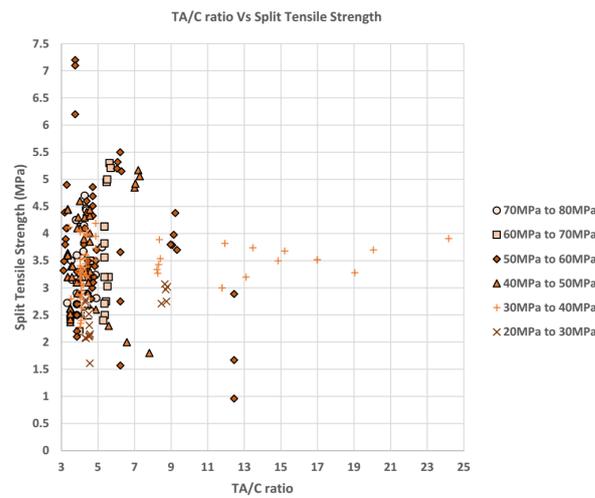
### 4.3. Effect of TA/C Ratio on Compressive Strength and Split Tensile Strength

In order to achieve proper packing density, the ratio of TA/C plays a key role. The particle size distribution of aggregates defines the formation of major voids in the system. Hence, the TA/C ratio plays a vital role in defining the fresh and hardened properties of the system. It is observed from Figure 6 that an increase in the TA/C ratio results in a decrease in compressive strength. This is because there is lesser binding content with an increase in TA content, which result in more pores. Most of the researchers with irrespective compressive strength of SCC opted for a TA/C ratio between 3 and 7. The literature with a TA/C ratio greater than 9 had a compressive strength in the range from 30 to 40 MPa.



**Figure 6.** Effect of TA/C ratio on various compressive strengths of SCC concrete with recycled aggregate according to the literature.

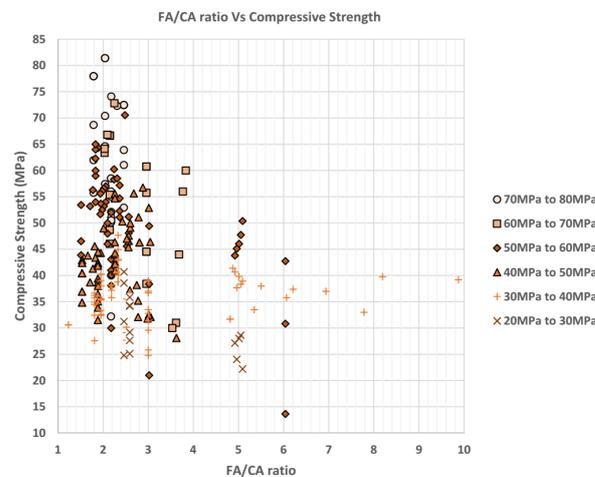
Similar to compressive strength behavior, with an increase in TA/C ratio there is a decrease in split tensile strength that is observed. However, the optimum ratio for TA/C ratio with respect to split tensile strength is observed from 3 to 5. Irrespective of SCC grade and with respect to compressive strength, the split tensile strength decreases with an increase in the TA/C ratio. There is no such sudden reduction in split tensile strength such as compressive strength when there is an increase in the TA/C ratio (Figure 7).



**Figure 7.** Effect of TA/C ratio on various split tensile strengths of SCC concrete with recycled aggregate according to the literature.

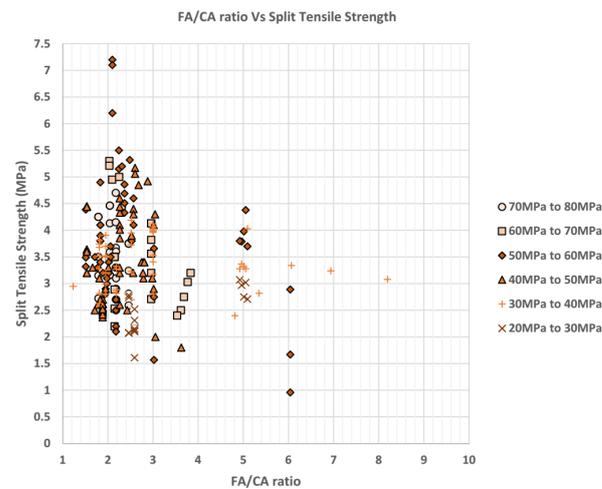
**4.4. Effect of FA/CA Ratio on Compressive Strength and Split Tensile Strength**

Most researchers used FA/CA in the ratio of 1.5 to 3.0 and this is observed in Figure 8. An increase in the ratio results in a decrease in compressive strength because the higher amount of fine content results in forming weak zones and stresses will transfer through this weaker zone while loading. When FA/CA ratio is greater than 5.0, it is found that the grade of concrete is below 40 MPa.



**Figure 8.** Effect of FA/CA ratio on various compressive strengths of SCC concrete with recycled aggregate according to the literature.

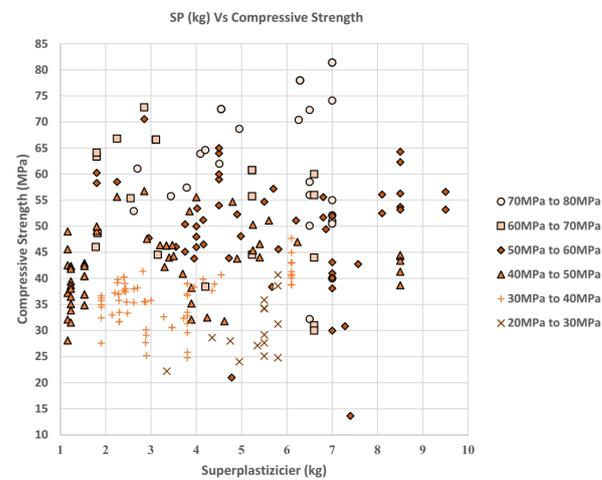
Split tensile strength of SCC with recycled aggregates initially increases with an increase in FA/CA ratio and this is observed in Figure 9 to 2.1 and, afterwards, the split tensile strength starts decreasing. On the basis of split tensile strength, the optimum FA/CA is observed from 1.5 to 3.0. Even high strength concrete with an FA/CA ratio greater than 3.0 also possesses lower split tensile strength and this is observed in the literature. Even though family V and VI possess lower compressive strength, the split tensile strength seems to be in the range from 2.5 MPa to 4.0 MPa when the FA/CA ratio is greater than 5.0.



**Figure 9.** Effect of the FA/CA ratio on various split tensile strengths of SCC concrete with recycled aggregate according to the literature.

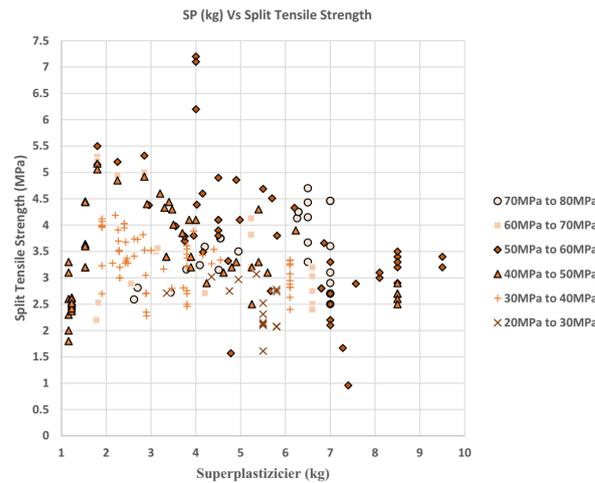
*4.5. Effect of Superplasticizer Weight on Compressive Strength and Split Tensile Strength*

For Family I, II, and VI, with an increase in the SP, there is a corresponding increase in compressive strength that is observed in Figure 10. There is no strong relationship exhibited between SP and compressive strength for Family III and V. However, for family IV, initially, the strength increases with an increase in SP to 3 kg and, after that, there is a decrease in compressive strength that is observed.



**Figure 10.** Effect of Superplasticizer weight on various compressive strengths of SCC concrete with recycled aggregate according to the literature.

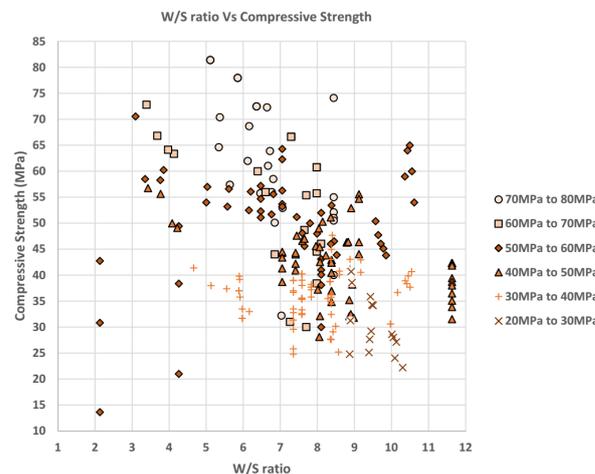
Split tensile strength increases with an increase in SP of the mix for the family is observed from Figure 11. For family II, IV, and VI, there was no constant relationship between the SP of mix and split tensile strength. For family III and V, initially, there was an increase in split tensile strength with an increase in SP and, after that, there was a decrease in split tensile strength that is observed.



**Figure 11.** Effect of Superplasticizer weight on various split tensile strengths of SCC concrete with recycled aggregate according to the literature.

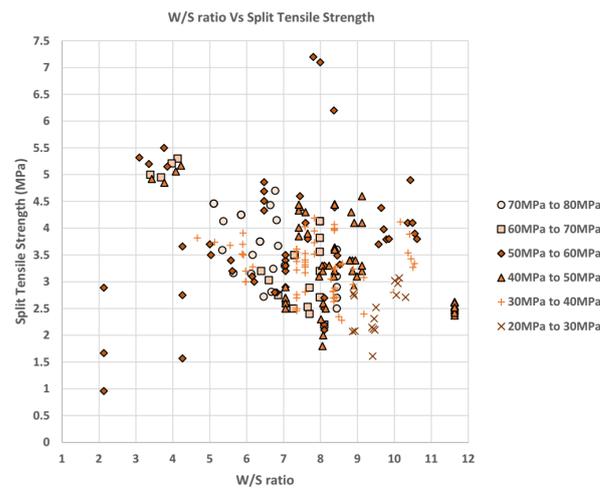
*4.6. Effect of W/S on Compressive Strength and Split Tensile Strength*

Most of the researchers used the W/S ratio in the range from 5.0 to 10.5. For the family I mix, the W/S ratio lies in between 5.0 and 8.5 and, for the family II mixes, the ratio reduced to the range between 3.5 and 8.0. For family III mixes, the W/S ratio was in the range between 2.13 and 10.61 and, for the family IV mixes, the W/S ratio was in the range between 3.43 and 11.63. For the family V mixes, the W/S ratio was in the range between 4.66 and 11.63 and, for family VI mixes, the W/S ratio is in the range between 8.9 and 11.0. With an increase in the W/S ratio, there is a decrease in compressive strength for the family I and II and there is no constant relationship between the W/S ratio and compressive strength for other families is observed from Figure 12.



**Figure 12.** Effect of W/S ratio on various compressive strength of SCC concrete with recycled aggregate according to the literature.

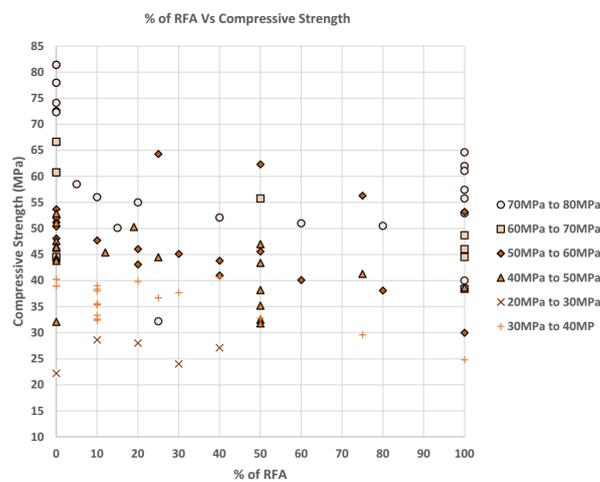
The lower the W/S ratio results in higher split tensile strength (greater than 4.75 MPa) for family II and IV. Initially, split tensile strength increases with an increase in W/S ratio for family III to 8.0 and after that there is a decrease in split tensile strength. For other families, there is no constant relationship exhibited between the W/S ratio and the split tensile strength of SCC is observed from Figure 13.



**Figure 13.** Effect of W/S ratio on various split tensile strength of SCC concrete with recycled aggregate according to the literature.

4.7. Effect of the Percentage of RFA on Compressive Strength and Split Tensile Strength

From Figure 14, it is observed that the higher level replacement for natural fine aggregate is performed below 20% replacement level and most family I, II, and III replacement levels are performed below 10%. One-hundred percent replacement of natural fine aggregate by RFA is observed in family I and II. Natural fine aggregate replacement level in between 10% to 80% by RFA is performed for family IV, V, and VI.



**Figure 14.** Effect of the percentage of RFA on various compressive strengths of SCC concrete with recycled aggregate according to the literature.

Split tensile strength in the range of 2.5 MPa to 5.0 MPa is observed for a lower level of replacement of natural aggregate by RFA and this is observed in Figure 15. For 100% replacement of natural fine aggregate by RFA, the result is a decrease in split tensile strength to the range from 2.0 MPa to 3.5 MPa.

4.8. Effect of the Percentage of RCA on Compressive Strength and Split Tensile Strength

Compared to the replacement of natural fine aggregates, a number of researchers performing the replacement of natural coarse aggregate is higher. The replacement of natural coarse aggregate by RCA is within the range of 20% to 60% and this is conducted more frequently by researches and it is found that the compressive strength lies within the range of 25 MPa to 65 MPa from Figure 16. One-hundred percent replacement of natural

coarse aggregates by RCA is performed by more researchers and its results in compressive strength lies within the range of 25 MPa to 60 MPa.

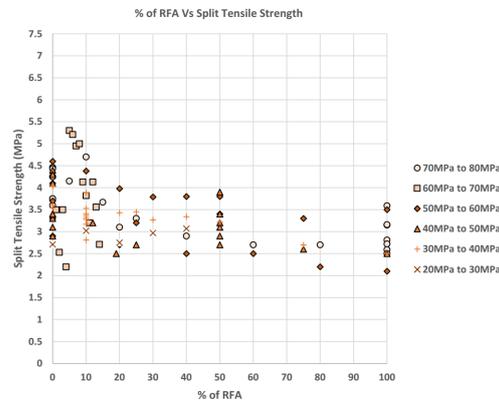


Figure 15. Effect of the percentage of RFA on various split tensile strengths of SCC concrete with recycled aggregate according to the literature.

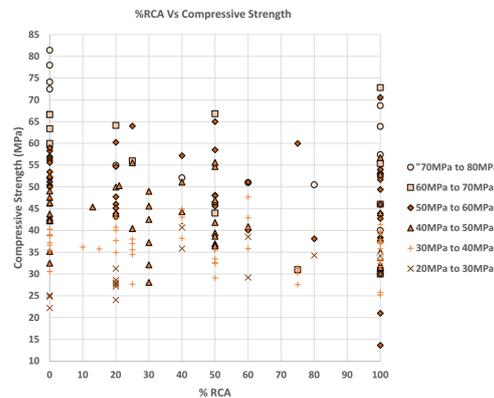


Figure 16. Effect of percentage of RCA on various compressive strengths of SCC concrete with recycled aggregate according to the literature.

Split tensile strength varies in the range of 2.0 MPa to 5.0 MPa for the 20% to 60% replacement level of natural coarse aggregates by RCA and this is observed in Figure 17. One-hundred percent replacement of natural coarse aggregates by RCA results in split tensile strength within the range of 2.0 MPa to 4.0 MPa.

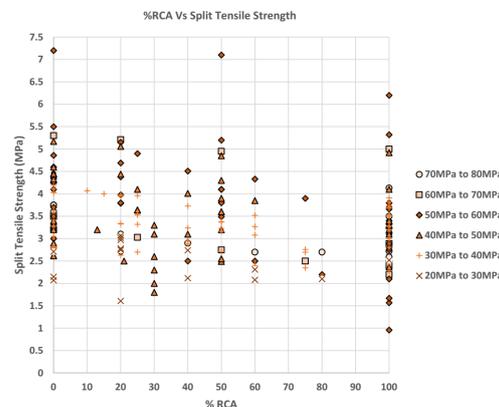
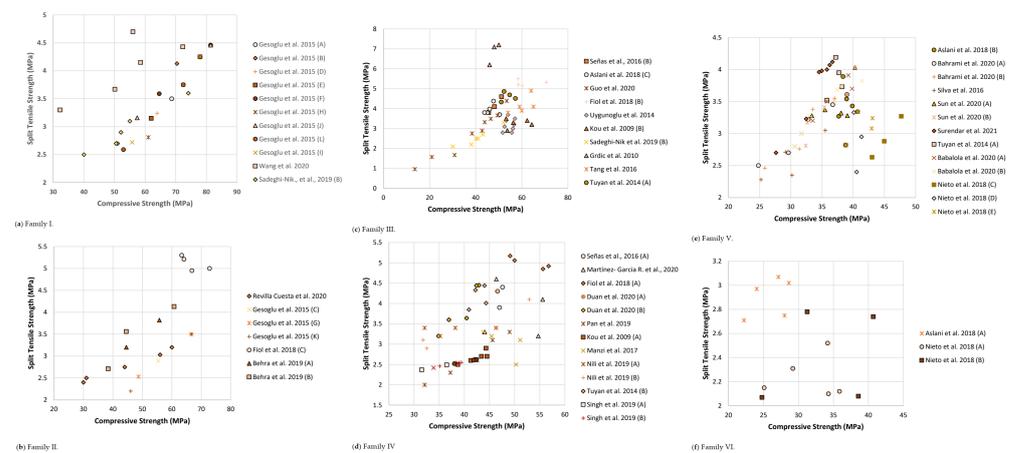


Figure 17. Effect of percentage of RCA on various split tensile strength of SCC concrete with recycled aggregate according to the literature.

## 5. Relation between Compressive Strength and Split Tensile Strength

Two most important parameters considered for the analysis and design of concrete members are compressive strength and split tensile strength [100]. Most of international design codes and researchers utilizes compressive strength as a base for the design and understanding of concrete properties [100]. Hence, most of mechanical properties are expressed as a function of compressive strength. Even several codes and researchers proposed several models for the relationship among mechanical properties and compressive strength. However, there are limited studies regarding the development of split tensile strength gain or loss with respect to the compressive strength of concrete. An attempt is made to understand the development of split tensile strength gain or loss with respect to different compressive strength grades of SCC and this is shown in Figure 18.



**Figure 18.** Relationship between compressive strength and split tensile strength which belongs to different families of SCC with RA according to the literature.

In Figure 18a, it is observed that for family I, the higher compressive strength corresponds to higher split tensile strengths and this condition is not validated by Wang et al., 2020 [80]. There is no gathering in relationship between compressive and split tensile strength and the relationship is distributed evenly. Similar to Figure 18a, there is even distribution of relationship which is observed for family II and is noted in Figure 18b. In a few of the cases where compressive strength is lower, higher split tensile strength is simultaneously noted. For family III, cluster formation is observed between compressive strength (range of 40 to 60 MPa) and split tensile strength (range of 2.5 MPa to 5 MPa) in Figure 18c. Several researchers obtained the highest and lowest split tensile strengths from this particular family. For family IV, most of researchers observed that there is non-linear relationship between compressive and split tensile strength as noted in Figure 18d. Distributed cluster formation in the relationship between compressive and split tensile strength for family V is observed in Figure 18e. There is no standard relationship between compressive and split tensile strength for family VI, as is observed in Figure 18f.

## 6. Conclusions

An intensive review on the impact of design parameters was conducted in order to make a simplified design procedure for the design mix of SCC made with recycled aggregates. The overall summarized report on the review is stated below:

- Increase in W/C ratio results in a decrease in compressive strength and split tensile strength. A W/C ratio greater than 0.6 is observed for Family V and VI. Split tensile strength greater than 4.5 MPa is obtained for Family II, III, and IV with a lower W/C ratio.
- W/B ratio less than 0.30 produces higher compressive strength and, simultaneously, higher split tensile strength. Further increase in the W/B ratio results in a decrease in compressive strength and split tensile strength.

- The lower the TA/C ratio is, the higher the compressive strength will be. However, there is a controversial result observed with respect to split tensile strength. When the TA/C ratio decreases in compressive and split tensile strength, the optimum range for TA/C ratio with respect to compressive and split tensile strength is 3 to 9.
- For most of the literature, it was found that FA/CA ratio lies in the range of 1.5 to 3.0 for compressive and split tensile strength. There is no constant relationship between strength and FA/CA ratio but it plays a vital role in fresh concrete properties for SCC.
- There is no constant relationship between SP and strength for SCC.
- When the W/S ratio is lower, the compressive and split tensile strength becomes higher. Higher W/S ratio results in lower compressive and split tensile strength.
- Higher compressive and split tensile strength is obtained for the lower-level replacement of NFA by RFA. However, 100% replacement of NFA by RFA results in compressive strength in a range of 40 MPa to 65 MPa and split tensile strength in a range of 2.5 MPa to 3.5 MPa.
- Higher compressive strength is obtained for 100% replacement of NCA by RCA. Most researchers had used the replacement of NCA by RCA up to 60% relative to the obtained compressive strength of more than 35 MPa. The increase in replacement of NCA by RCA results in a decrease in split tensile strength.
- For several families, there is cluster formation in family III and V observed for compressive and split tensile strength. For family I, II, and IV, there is linear relationship and family VI demonstrates a non-linear relationship.

Detailed investigation on the effect of design parameters on the strength properties of SCC with recycled aggregate will help researchers and engineers to develop a minimum requirement for a SCC mix with recycled aggregates. It also helps to develop a guideline for field engineers and assists the progress of several international standards and codes.

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