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Laboratory Investigations on Fracture Toughness of Self-compacting Concrete Containing Recycled Materials

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ABSTRACT

This article investigates the fracture toughness in self-compacting concrete containing different percentages of recycled concrete materials using edge-notched disc bend (ENDB) samples. For this reason, 0, 25, 50, 75 and 100 percent of recycled aggregate were used instead of natural aggregate in the mixing designs. To obtain the fracture toughness, ENDB samples were used under loading of mixed mode I/III and pure modes I and III. Cubic samples were also used to obtain compressive strength. The results show that the compressive strength of the samples has a direct relationship with the fracture toughness and the reverse ratio with the percentage of recycled concrete materials. Also, samples containing 25% recycled materials have the highest compressive strength and fracture toughness. Furthermore, as the recycled percentage of the samples increases, the performance of samples against shear forces and compressive strength is reduced.

Keywords: Fracture toughness, Mixed mode I/III, Recycled materials, Self-compacting concrete, ENDB samples.

INTRODUCTION

Concrete is known as the most widely used construction material due to its unique features, such as easy access, low price and convenient use. Over the last few decades, both government agencies and the construction industry have recognized the importance of recycling old construction materials. This is due to the rising expense of waste storage and the depletion of natural resources. Among the various construction waste materials, old concrete stands out as a potential source of recycled aggregate that can meet the quality standards necessary for civil-engineering applications with moderate performance demands (Choi, 2019). As a brittle material, concrete becomes more brittle with increasing strength due to its low tensile strength and poor performance against crack propagation, which is the main disadvantage of unreinforced concrete (Afroughsabet & Ozbakkaloglu, 2015). The presence of primary cracks and fractures in stone, concrete and other engineering materials is inevitable. One of the special characteristics of each material causes concrete structures to break faster under mechanical loads or other environmental factors (Ayatollahi & Aliha, 2008).

Therefore, studying the fracture mechanics of concrete helps increase the structure's useful life. Crack formation and propagation are important for many science and engineering applications. Crack growth functions from a microscopic point of view due to the dissociation of the molecular bonds of the crack tip. The presence of many pores and cracks causes rock fractures. Microcracks develop and expand when an external force is applied, microfractures form and rock breaks (Feng, Kang, Chen, Liu & Wang, 2018). Fracture mechanics focus on the fracture mechanism of cracked materials, which describes the behavior of cracked materials using analytical solutions and experimental methods (Zarei, Kordani, Khanjari & Zahedi, 2022). The concrete cover, which has been used as an alternative to asphalt in recent years, has a longer life and durability, but it is not safe from the tensile stress caused by a load of car wheels. Based on the type of loading during the fracture process, depending on the geometry and loading on the samples, there are three main modes of crack propagation: mode I (opening mode, tensile mode), where the crack surfaces are separated in the direction perpendicular to the crack plane, mode II (shear mode), in which the crack surfaces slide in a direction perpendicular to the front edge of the crack and mode III (tear mode), where the crack surfaces move in a direction parallel to the front edge of the crack, see Fig.1. These modes together can create a hybrid mode and in Fig. 2, the effect of car-wheel load can be seen (Aliha, Bahmani & Akhondi, 2016). In recent years, many types of research in the field of fracture mechanics have been conducted by researchers to investigate fracture toughness. Undoubtedly, the progress and growth in fracture mechanics are due to a wide range of engineering problems that have strengthened such investigation.

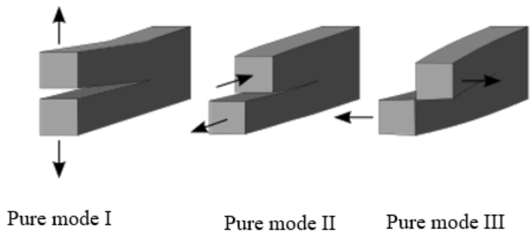

Figure (1): Different modes of loading (Kundu, 2008)

According to the definition of fracture mechanics, an unstable fracture occurs when the stress is concentrated near the crack tip. The ability of concrete to withstand and resist the initiation and propagation of cracks, also known as fracture toughness, is reached by one of the stress-intensity factors, K_I, K_{III} or the mixed mode (K_{eff}) which is also referred to as the crucial value (Kundu, 2008). Carpinteri studied the relationship between the tensile strength of concrete and cracks in the mixed-mode state by considering the effects of crack size and crack propagation in different sizes (Carpinteri, 1988). Mirsyar and Park, in their review, mentioned measures called the developed maximum tensile stress (MTS) and the extended maximum tangential strain (EMTSN), stating that the crack propagates in cement-sand mortar in the direction where the strain reaches its ultimate value (Mirsayar & Park, 2016). Also, in the review of concrete reinforcement with fibers, Carpinteri & Brighenti investigated the effects of the water-cement ratio on fracture resistance and other mechanical properties of concrete in the mixed-mode state (Carpinteri & Brighenti, 2010).

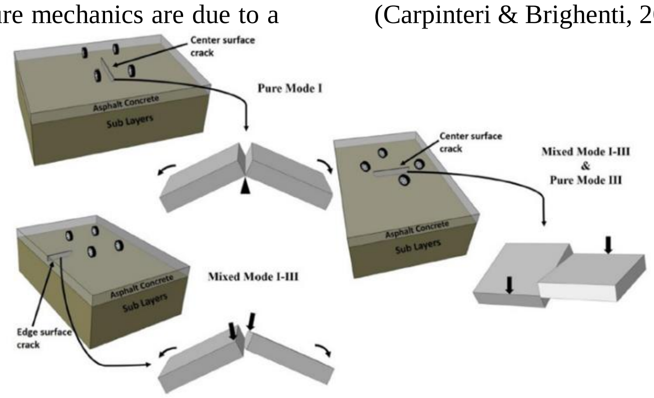

Figure (2): Applicability of the ENDB specimen for simulation of pure mode I, mixed mode I/III and pure mode III deformations in a top-down crack initiated in the surface of pavement structure and subjected to traffic loading (Aliha et al., 2016)

Khaneghahi et al. investigated the fracture toughness of mixed mode I/III on the asphalt mixture containing fibers and gilsonite. They concluded that gilsonite and especially fibers increase fracture toughness (Khanghahi & Tortum, 2018). Also, based on Shima Najjar et al.'s research, it can be understood that aging, water-to-cement ratio, bitumen-to-cement ratio and the amount of cement used can affect the behavior of cement emulsion asphalt mortar under fracture mode I/III. The results show that for both aged and non-aged samples (control), the highest fracture toughness is obtained in the pure tensile state (pure mode I) and with the increase in the proportion of mode III, the fracture toughness value decreases. The developed statistical models showed that increasing the A/C ratio affects mode I-, mode III-and mixed mode I/III-stress-intensity factors for fresh samples. However, for aged samples, the effect of A/C is observed in its relationship with W/C (Najjar, Moghaddam, Sahaf & Aliha, 2022).

Consequently, due to the importance of protecting the environment, recycled materials are becoming increasingly popular, since, according to reports, the construction industry consumes approximately 20%-50% of all natural resources and 40% of all energy (Cooper, Unit & Branch, 2015; Vasilca et al., 2021). It should also be noted that cement production alone is responsible for 7% to 9% of CO_2 emissions worldwide (Monteiro et al., 2017). This research investigates the fracture behavior of self-compacting concrete containing recycled concrete materials .Despite prior research, this study illuminates the fracture behavior of self-compacting concrete incorporating varied percentages of recycled concrete materials. Additionally, it explores the influence of micro-silica and wollastonite in recycled samples. Its findings can serve as a guide for future studies, contributing insights into the potential utilization of different proportions of recycled aggregate in the construction industry, especially in concrete pavements.

Elastic Stresses around a Crack

According to the studies conducted by Williams (1957) on the distribution of stress around the crack tip and based on the concept of linear elastic fracture mechanics (LEFM) for the mixed mode I/III, see Fig. 3, the relationships related to the stresses created at the crack tip in loading mode I/III can be written as follows (Williams, 1957):

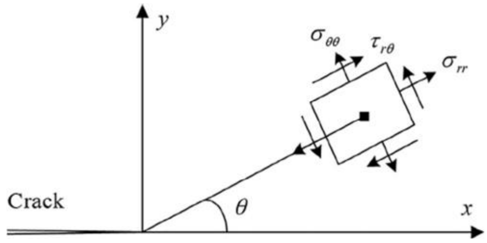

Figure (3): Crack-tip stress components in polar coordinates

$$\sigma_{rr} = \frac{K_1}{\sqrt{2\pi r}}\left[\frac{5}{4}\,cos\,\frac{\theta}{2} - \frac{1}{4}\,cos\,\frac{3\theta}{2}\right] + TCos^2(\theta) \qquad (1)$$

$$\sigma_{\theta\theta} = \frac{K_1}{\sqrt{2\pi r}}\left[\frac{3}{4}\,cos\,\frac{\theta}{2} + \frac{1}{4}\,cos\,\frac{3\theta}{2}\right] + TSin^2(\theta) \qquad (2)$$

$$\sigma_{r\theta} = \frac{K_1}{\sqrt{2\pi r}}\left[\frac{1}{4}\,cos\,\frac{\theta}{2} + \frac{1}{4}\,cos\,\frac{3\theta}{2}\right] - TSin(\theta)TCos(\theta) \qquad (3)$$

$$\tau_{r\theta} = \frac{K_{III}}{\sqrt{2\pi r}}\left[Cos\,\frac{\theta}{2}\right] \qquad (4)$$

$$\tau_{rz} = \frac{K_{III}}{\sqrt{2\pi r}}\left[Sin\,\frac{\theta}{2}\right] \qquad (5)$$

$$\sigma_{zz} = \gamma\,[\sigma_{rr} + \sigma_{\theta\theta}] \qquad (6)$$

In the above equations, factors K_I and K_{III} are the stress-intensity factors in modes I and III, respectively. Factor θ and r are the angle with respect to the crack plane and distance from crack tip to element dxdy, respectively, σ_{rr}, $\sigma_{\theta\theta}$, $\sigma_{r\theta}$ and σ_{zz} stand for the plane stress, while τ_{rz} and $\tau_{r\theta}$ are the shear stress.T is the stress independent of r and θ, while γ is the Poisson's ratio. They are of great importance in analyzing problems related to fracture mechanics. The general form of showing the stress-intensity factors is as shown in Equation (7).

$$K_i = Y_i\sigma\sqrt{\pi a} \qquad i=I,II,III \qquad (7)$$

where: σ is the applied stress on the piece, a is the crack depth, Y_i is the engineering coefficient and a is the crack length for edge cracks or half for internal cracks. The unit of K_i (stress-intensity factor) in the international system (SI) is MPa√m.

For simple geometries and loads, the value of Yi and, as a result, the value of stress-intensity factors can be calculated through analytical methods. The values of stress-intensity factors for such parts are provided in various handbooks and references.

EXPERIMENTAL STUDY

Materials

This research used natural and recycled aggregates with a nominal maximum size of aggregate of 12.5 mm and Type-II cement to make concrete. The granulation curve of the aggregates is given in Figs. 4 and 5. The nominal water absorption of natural aggregate and recycled aggregate is 1.1% and 5.9%, respectively, which is expected due to old mortar in recycled aggregate. Also, due to the self-compacting nature of concrete, super-plasticizer and fine aggregate are used to increase the efficiency of concrete. The flowability of SCC to resist segregation is greatly influenced by several factors, including the water-cement (w/c) ratio, viscosity-modifying agents (VMAs), size of aggregates and the amounts of super-plasticizers (SPs) (Kanagaraj et al., 2023). Super-plasticizers and fine aggregate are essential components in concrete. SPs improve workability and flowability, leading to faster construction times and improved quality of finished products. Fine aggregate enhances the strength, durability and workability of concrete and, when combined with SPs, can create SCC which is highly flowable and can reduce construction times and costs. Recycled aggregate is the product of crushing concrete samples with an average strength of 30 MPa, by a stone crusher and a sand machine

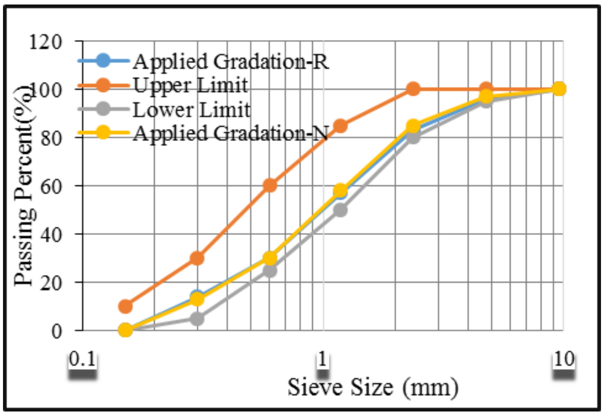

Figure (4): Granulation curve of natural and recycled sand

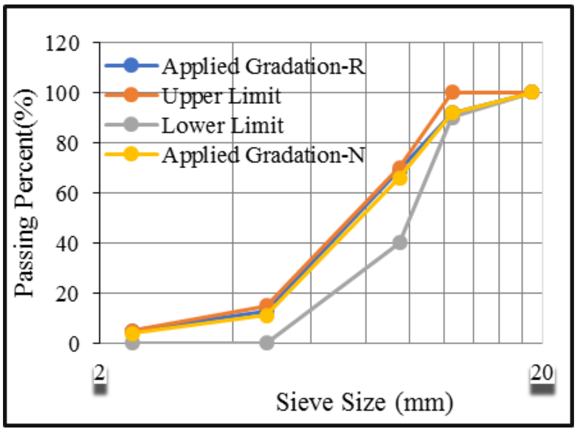

Figure (5): Granulation curve of natural and recycled gravel

The Experimental Program

In this study, we employed five distinct types of concrete mixing composition, as outlined in Table 1. Each type incorporated varying percentages of recycled aggregates, ranging from 0% to 100%, alongside natural aggregates. Furthermore, the natural aggregates were utilized in different proportions, also ranging from 0% to 100% of recycled aggregates. The primary objective was to investigate the impact of these aggregate variations on concrete properties. To enhance workability, beach sand was introduced in varying percentages. The rounded corners of the beach sand aimed to increase the overall workability of the concrete. The samples were prepared using molds measuring 150 mm in diameter and 40 mm in thickness (refer to Fig. 6). To assess the concrete's performance, a 16-mm crack was precisely induced at the center of each sample using a radiological film.

After the samples were cured, a fracture test was performed for 28 days. Also, to compare the compressive-strength results with the fracture-test results, 10-cm cubic samples were made and subjected to a compressive-strength test after curing for 28 days in lime water. Moreover, Fig.7 illustrates the process of preparing the samples and conducting relevant tests.

Table 1. Details of mixing composition

	AE	SP	water	BS	cement	FA	RFA	CA	RCA
RA 0	1.45	4.37	195.62	108.10	437.00	1083.30	—	532.38	—
RA 25	1.45	4.37	195.62	108.10	437.00	812.48	270.83	399.29	133.10
RA 50	1.45	4.37	195.62	108.10	437.00	541.65	541.65	266.19	266.19
RA 75	1.45	4.37	195.62	108.10	437.00	270.83	812.48	133.10	399.29
RA 100	1.45	4.37	195.62	129.70	437.00	—	1083.30	—	532.38

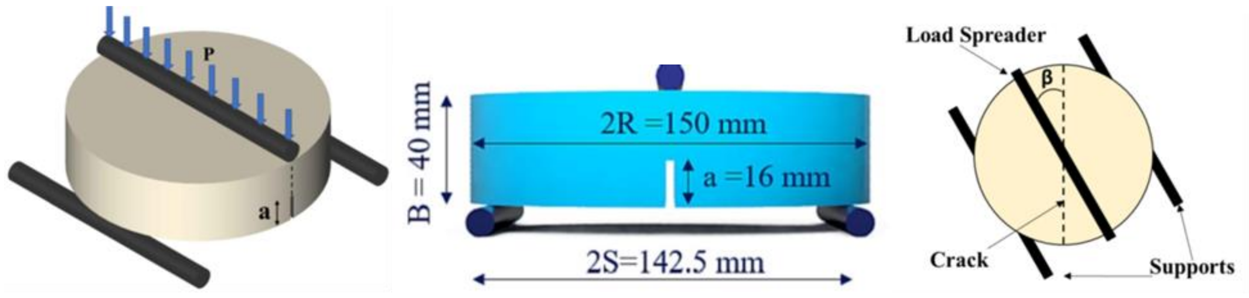

Figure (6): Geometry ENDB specimen and loading modes I, III and I/III (Murali et al., 2023)

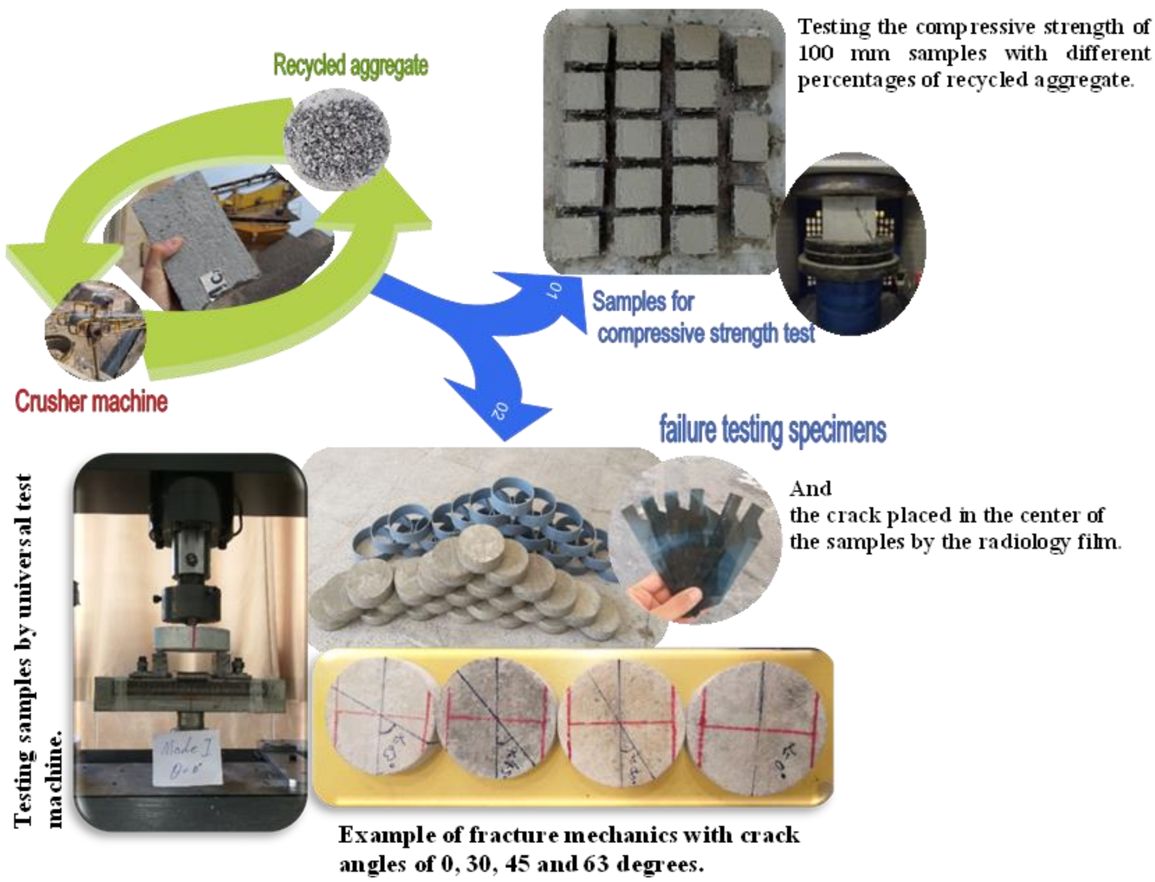

Figure (7): The preparation process for the cracked ENDB specimens

Figure (8): The UTM machine used for the tests

Before the test, the angles and location of the crack relative to the loading axis were determined as β = 0°, 30°, 45° and 63° for pure mode I, mixed mode I/III and pure mode III. As the angle β increases, the fracture modes change. The refraction angles used in this research were 0,30, 45 and 63 degrees. Also, when β has a non-zero value, the samples are subjected to loading with in-plane and out-of-plane shear deformations and the corresponding fracture toughness is KI and KIII, respectively. As a result, three-dimensional stress states are created along the crack region. In order to achieve mode-III fracture, angle β should be maintained between 60 and 65 degrees. In this study, the angle chosen for this mode III was 63 degrees. Angles between 0° and 63° indicate fracture of mixed modes. This study used angles of 30 and 45 degrees to evaluate the fracture toughness with mixed modes I/III. The UTM machine was used for the tests, the loading speed was 3 mm/min and the test was carried out at ambient temperature, see Fig. 8.

Fracture-test Data

Table 3 shows the fracture-test results on disc samples under different loading conditions, including pure mode I, mixed mode I/III and pure mode III. Also, the results include different percentages of recycled concrete; 0, 25, 50 and 100 percent by weight of aggregate. The pcr parameter indicates the ultimate fracture load and the dimensionless parameter M^e, called mixity mode, is 1 for pure mode I and 0 for pure mode III and is obtained from Equation (8).

$$M^e = \frac{2}{\pi}\, tan^{-1}\left(\frac{Y_I}{Y_{III}}\right). \tag{8}$$

The critical stress-intensity factors were obtained using the geometric-shape factors and the final-load value from the following relationships (Pirmohammad & Bayat, 2016).

$$\sigma = \frac{6SP_{cr}}{RD^2}\ , (MPa) \tag{9}$$

$$K_{\mathrm{I}=}\ \sigma\sqrt{\pi a}Y_{\mathrm{I}}\ , (MPa) \tag{10}$$

$$K_{\mathrm{III}=}\ \sigma\sqrt{\pi a}Y_{\mathrm{III}}\ , (MPa) \tag{11}$$

In the relations above, s is the half-span of the supports, P_{cr} is the final critical load, K_I and K_{III} are the stress-intensity factors of modes I and III, a is the crack depth and Y_I and Y_{III} are the geometric-shape factors of modes I and III.

The K_{eff} parameter is the effective stress-intensity factor, which is obtained from the K_I and K_{III} fracture-toughness values according to the following relationship. Also, the geometrical-shape factors for each of the failure modes are given in Table 2.

$$K_{eff=}\sqrt{{K_{\mathrm{I\,f}}}^2 + {K_{\mathrm{III\,f}}}^2}\ , (MPa) \tag{12}$$

Table 2. Geometry factors for the loading modes (Pirmohammad & Bayat, 2016)

α (deg)	M^e	Y_I	Y_{III}
0	0	0.309	0
30	0.220	0.215	0.0773
45	0.418	0.120	0.0924
63	1	0	0.0821

Table 3. Average critical stress-intensity factors (K_{If} and K_{IIIf}) calculated from the experimental results

Mixture Id.	Mode I			Mixed mode I/III			Mixed mode I/III			Mode III		
	β = 0°			β = 30°			β = 45°			β = 63°		
	K_{If}	K_{IIIf}	K_{eff}	K_{If}	K_{IIIf}	K_{eff}	K_{If}	K_{IIIf}	K_{eff}	K_{If}	K_{IIIf}	K_{eff}
EWR 0	4.99	0.00	4.99	5.41	1.94	5.75	4.24	3.67	5.61	0.00	4.43	4.43
EWR 25	5.76	0.00	5.76	5.75	2.07	6.11	4.26	4.16	5.96	0.00	4.88	4.88
EWR 50	4.78	0.00	4.78	5.35	1.80	5.64	3.71	3.55	5.13	0.00	4.00	4.00
EWR 75	4.76	0.00	4.76	5.22	1.74	5.51	4.36	2.85	5.21	0.00	4.14	4.14
EWR 100	4.55	0.00	4.55	5.01	1.68	5.28	4.33	2.72	5.11	0.00	3.76	3.76

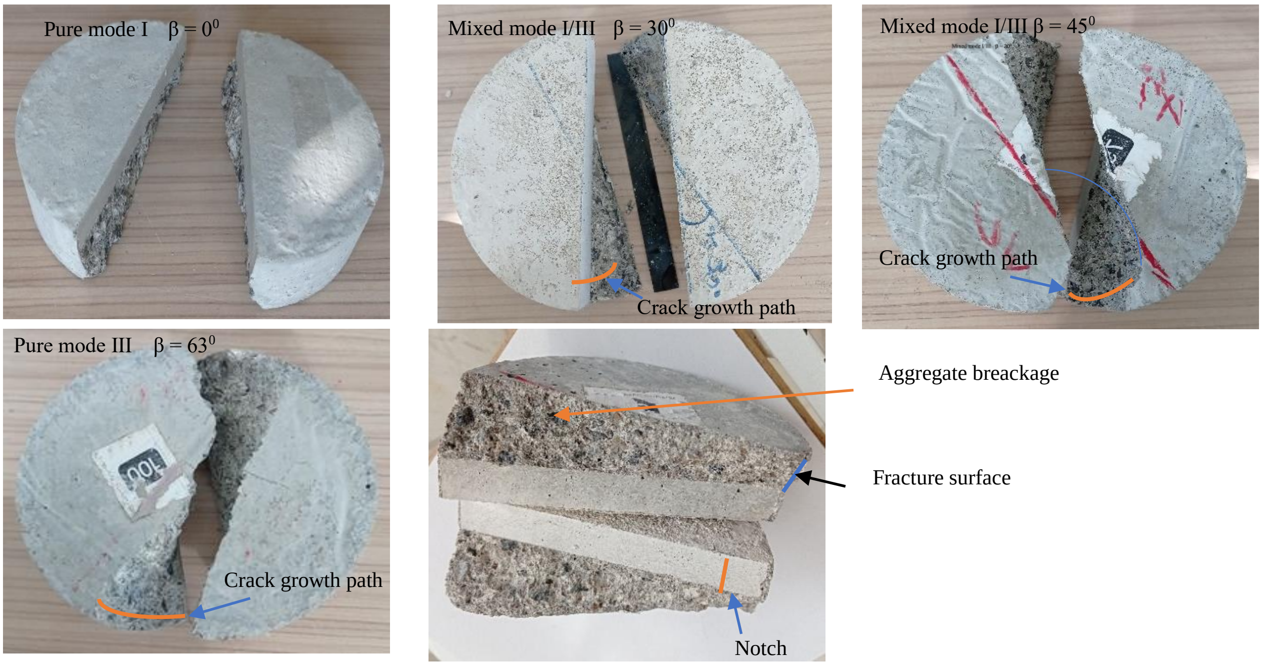

Figure (9): ENDB specimens after fracture tests

RESULTS AND DISCUSSION

In this part of the research, a series of rheological tests have been conducted on different designs of concrete to investigate the effect of the simultaneous use of natural and recycled aggregates. The results are given in Table 4. By examining the results and Figures 10 and 11, it is clear that the slump flow is decreasing with the increase in recycling percentage, but despite this, the results of all the concrete designs are within the standard range. It should be noted that by increasing the volume of fine aggregate and the dosage of super-lubricant, it is possible to increase the grade of this concrete according to the project's needs. However, it is important to control the fact that the possibility of separation will increase with the increase of slump. Also, the rheological behavior of concrete in J-Ring and J-Ring slump tests is according to the slump test (C.A., 2014; standard).

Table 4. Slump flow and J-ring results

Mixture Id.	T 50 (S)	Slump (mm)	J-ring (h2-h1) (mm)	J-ring (mm)
RA 0	4.43	689	7.5	649
RA 25	4.6	654	8	611
RA 50	4.69	635	8	602
RA 75	4.81	617	9.5	578
RA 100	5.01	694	10	570

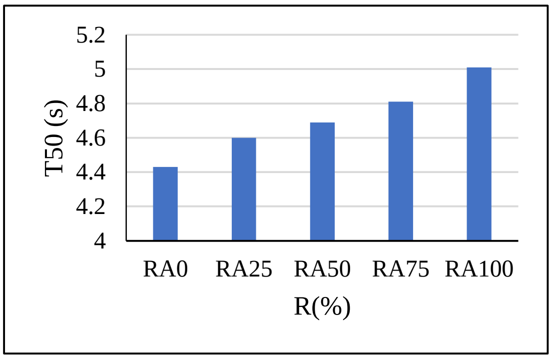

Figure (10): T 50 slump-test results

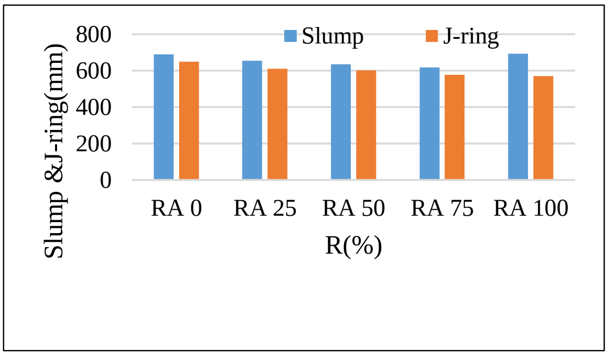

Figure (11): Slump- and J-ring-test results

According to the fracture modes, the fracture toughness was calculated based on the maximum force obtained from the fracture test, along with the shape and dimensions of the samples (Table 2). The effect of recycled concrete materials on the fracture toughness of SCC samples can be seen in Fig. 12. The highest fracture toughness in samples containing 25% recycled concrete materials with a value of 6.11 and M^e = 0.220 mixed mode I/III is obtained. The fracture toughness decreases with the increase in recycled concrete materials. The main reason for this is the poor performance of the aggregates of recycled concrete materials due to their fine grain against the shear force in pure mode III. So, the lowest fracture toughness is obtained in samples containing 100% recycled materials; also, by examining Fig.12, it can be seen that adding more than 25% of recycled materials harms fracture toughness in all loading modes. The higher fracture toughness in samples containing 25% recycled concrete than samples without recycled materials is wollastonite and micro-silica in recycled concrete.

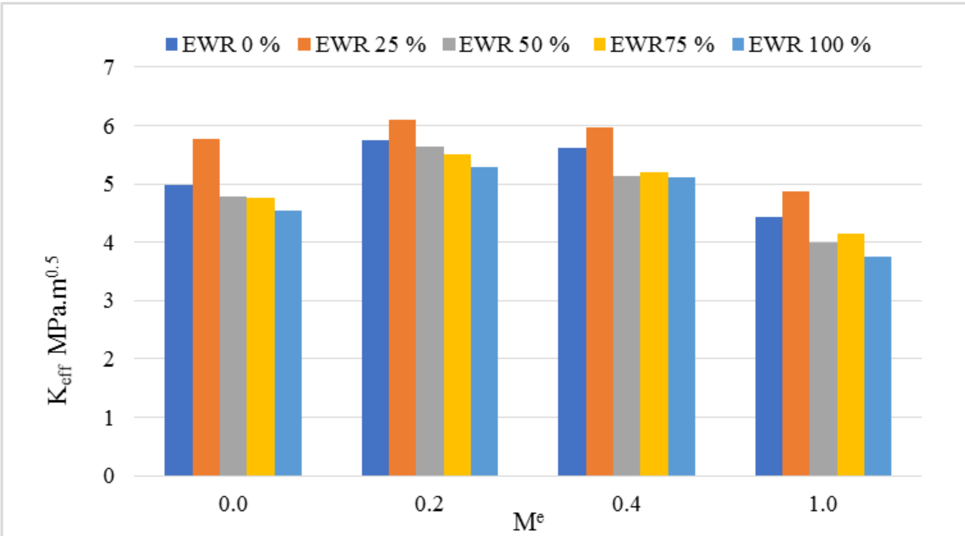

Figure (12): Variation of the fracture toughness K_{eff} *versus* the mode of loading M^e for the control concrete and EWR dosages

Fig.13 shows the fracture toughness of mode I compared to mode III for different percentages of recycled materials. Fig. 13 shows that in the recycled percentage of 100%, the highest fracture resistance against tensile forces is obtained compared to shear force. The main reason for this is a high percentage of recycled fine-aggregate materials, which are weak against shear forces. Also, samples without recycled concrete materials show the highest fracture resistance against shear forces. The main parameters, such as thickness, sample radius, crack size and loading temperature, are involved in this matter and should be in the right range.

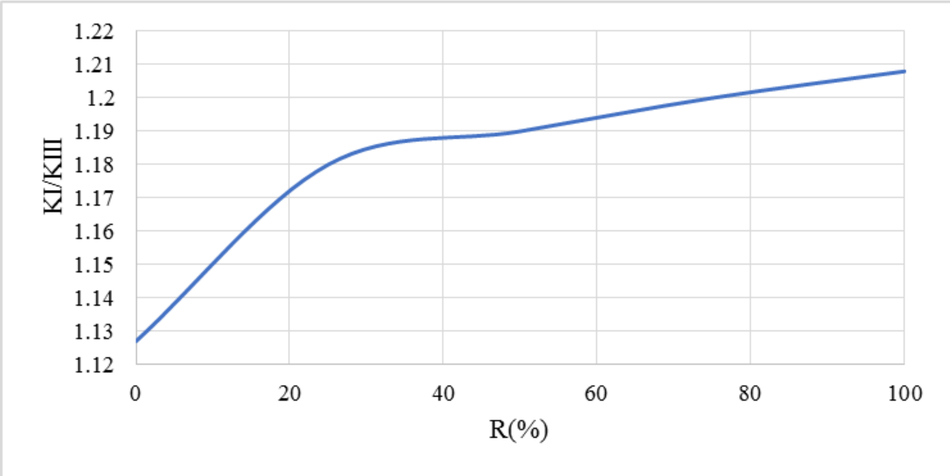

Figure (13): Variations of fracture toughness ratio K_I/K_{III} with recycled materials for different designs of concrete mix

The results of the 28-day compressive strength of SCC samples have a direct relationship with the fracture toughness and the reverse ratio with the percentage of recycled concrete materials, see Fig. 14. With 25% recycled concrete materials, the highest compressive strength is 42.45 MPa after 28 days. Moreover, the compressive strength has decreased with the increase in recycled materials. The reason for this is the existence of many fine-grained materials, which are less strong against compressive forces. On the contrary, the tensile strength, fracture toughness of mode I and the 28-day compressive strength of the samples have a perfect ratio with the fracture toughness of pure mode III. Increasing the number of recycled materials decreases compressive strength and fracture toughness, especially in pure mode III.

Regarding the failure mechanism and the reasons for increasing or decreasing the fracture toughness in terms of the diameter and size of the materials used in the samples, it can be concluded that the higher the fracture surface of the material in the crack growth path, the higher the fracture toughness, In the case of the minimum percentage of fine-grained and coarse-grained materials, it is mandatory to comply with the standard and denser granulation is considered. Due to having a special surface and high adhesion, they show better performance against tensile forces. As a result, K_I is higher in them. Usually, the ratio of K_I/K_{III} increases with the increase of fine-grained materials; however, in samples that have more coarse-grained materials than fine-grained materials, they show resistance to crack growth in K_{III} mode and shear force. Regarding the results of compressive strength and fracture toughness, in addition to the size of the materials, having a dense granulation for high locking and bonding between the materials shows a significant effect on the compressive strength and fracture toughness, such as in the amount of 25% of recycled materials and 75% of natural materials.

To check the correctness and validation of the results obtained in this article, it can be seen that the results obtained are entirely similar to the results of the research conducted by other researchers, such as Murali and Mirsyar, whose references are given in this article (Mirsayar & Park, 2016; Murali, Abid, Al-Lami, Vatin, Dixit & Fediuk, 2023).

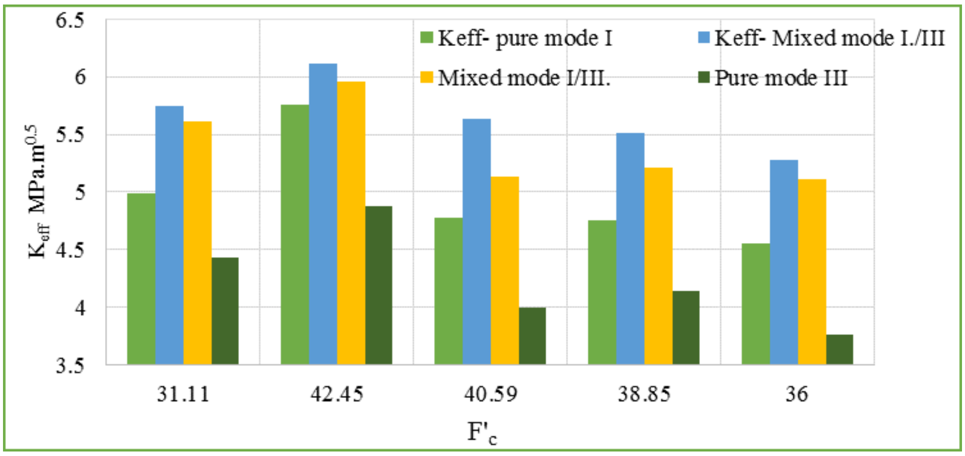

Figure (14): Comparison of effective stress-intensity factor values *versus* compressive strength of concrete

CONCLUSIONS

This research investigates the fracture toughness of SCC containing recycled concrete materials. The fracture tests of different percentages of recycled concrete materials (0%, 25%, 50%, 75% and 100%) were conducted. The following conclusions are drawn:

1. The fracture toughness in all fracture modes in samples containing 25% recycled concrete materials has the highest value compared to the other percentages of recycled concrete materials. The highest fracture toughness is obtained in the mixed mode I/III of the pure mode I and the pure mode III.
2. Increasing recycled concrete materials to more than 25% reduces fracture toughness. Moreover, this is true in all modes of fracture.
3. The lowest fracture toughness is obtained in 100% recycled concrete materials samples and at M^e=1.
4. The compressive strength of recycled SCC samples is directly related to the fracture toughness and inversely related to the percentage of recycled concrete materials. So, with the increase of compressive strength, the fracture toughness also increases.
5. The highest ratio of K_I and K_{III} is obtained in samples containing 100% recycled concrete materials due to the high percentage of recycled concrete materials (fine aggregate).
6. Using wollastonite and micro-silica improves the performance of recycled concrete materials in terms of fracture toughness and compressive strength.

Nomenclature

AE	Air Entrainment	M^e	mode mixity parameter
SP	Super-plasticizer	P	applied load
BS	Beach Sand	Pcr	critical applied load
FA	Fine Aggregate	S	location of loading supports
RFA	Recycled Fine Aggregate	Y_I, Y_{III}	mode I and III geometry factors
CA	Coarse Aggregate	a	crack inclination angle
RCA	Recycled Coarse Aggregate		
a	crack length	qeff	relatively mixed mode fracture toughness
K_{eff}	The effective stress intensity factor	K_{If}, K_{IIIf}	mode I and III stress intensity factors corresponding to the fracture load
K_I, K_{III}	mode I and III stress intensity factors	ENDB	Edge-notched disc bend

REFERENCES

Afroughsabet, V., and Ozbakkaloglu, T. (2015). “Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers". Construction and Building Materials, 94, 73-82.

Aliha, M., Bahmani, A., and Akhondi, S. (2016). “A novel test specimen for investigating the mixed mode I+ III-fracture toughness of hot-mix asphalt composites: Experimental and theoretical study". International Journal of Solids and Structures, 90, 167-177.

Ayatollahi, M., and Aliha, M. (2008). “On the use of Brazilian disc specimen for calculating mixed mode I-II-fracture toughness of rock materials". Engineering Fracture Mechanics, 75 (16), 4631-4641.

C.A. (2014). “Standard test method for slump flow of self-consolidating concrete". ASTM International, West Conshohocken, PA, USA.

Carpinteri, A. (1988). “Interaction between tensile-strength failure and mixed-mode crack propagation in concrete". Materials and Structures, 21, 403-409.

Carpinteri, A., and Brighenti, R. (2010). “Fracture behaviour of plain and fiber-reinforced concrete with different water contents under mixed-mode loading". Materials & Design, 31 (4), 2032-2042.

Choi, H. (2019). "Applicability evaluation of short concrete columns using recycled coarse aggregate in an existing column-design model." Jordan Journal of Civil Engineering, 13 (1).

Cooper, D., Unit, F., and Branch, E. (2015). “Energy efficiency for buildings". United Nations Environment Programme.

Feng, G., Kang, Y., Chen, F., Liu, Y.-W., and Wang, X.-C. (2018). “The influence of temperatures on mixed-mode (I+ II) - and mode II-fracture toughness of sandstone". Engineering Fracture Mechanics, 189, 51-63.

Kanagaraj, B., Anand, N., Andrushia, D., Mathews, M.E., Alengaram, J., Arulraj, P., and Kiran, T. (2023). "Mechanical properties and microstructure characteristics of self-compacting concrete with different admixtures exposed to elevated temperatures". Jordan Journal of Civil Engineering, 17 (1).

Khanghahi, S.H., and Tortum, A. (2018). “Determination of the optimum conditions for gilsonite and glass fiber in HMA under mixed-mode I/III loading in fracture tests". Journal of Materials in Civil Engineering, 30 (7), 04018130.

Kundu, T. (2008). “Fundamentals of fracture mechanics". CRC Press.

Mirsayar, M., and Park, P. (2016). “Mixed-mode brittle-fracture analysis of high-strength cement mortar using strain-based criteria". Theoretical and Applied Fracture Mechanics, 86, 233-238.

Monteiro, M., PJ, M.S.A., and Horvath, A. (2017). “Towards sustainable concrete". Nature Publishing Group.

Murali, G., Abid, S.R., Al-Lami, K., Vatin, N.I., Dixit, S., and Fediuk, R. (2023). “Pure-and mixed-mode (I/III)-fracture toughness of preplaced-aggregate fibrous concrete and slurry infiltrated fibre concrete and hybrid combination comprising nano-carbon tubes". Construction and Building Materials, 362, 129696.

Najjar, S., Moghaddam, A.M., Sahaf, A., and Aliha, M. (2022). “Aging effect on the mixed-mode (I/III) fracture toughness of cement-emulsified asphalt composite: Experimental and statistical investigation". Engineering Fracture Mechanics, 264, 108292.

Pirmohammad, S., and Bayat, A. (2016). “Characterizing mixed-mode I/III-fracture toughness of asphalt concrete using asymmetric disc bend (ADB) specimen". Construction and Building Materials, 120, 571-580.

Standard A. C1621. (2009). “Standard test method for passing ability of self-consolidating concrete by J-ring". West Conshohocken, PA, 2003, DOI: 10.1520/C1621.

Vasilca, I.-S., Nen, M., Chivu, O., Radu, V., Simion, C.-P., and Marinescu, N. (2021). “The management of environmental resources in the construction sector: An empirical model". Energies, 14 (9), 2489.

Williams, M.L. (1957). “On the stress distribution at the base of a stationary crack".

Zarei, M., Kordani, A.A., Khanjari, M., and Zahedi, M. (2022). “Evaluation of fracture resistance of asphalt concrete involving calcium lignosulfonate and polyester fiber under freeze–thaw damage". Theoretical and Applied Fracture Mechanics, 117, 103168.