Construction and Building Materials 282 (2021) 122711

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of waste glass and curing aging on fracture toughness of self-compacting mortars using ENDB specimen

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HIGHLIGHTS

- Fracture toughness parameters were determined for all waste glass self-compacting mortars using ENDB specimen.
- WG aggregate (0% to 100%) and curing aging (14, 28 and 56 days) affect the fracture toughness of mortar.
- The use of 20% and 40% WG aggregate will increase the fracture toughness and the critical load of mixture.
- Increasing the curing age has the greatest effect on the pure mode 3.
- The pure mode 3 is the most critical loading mode for mortars containing WG.

ARTICLE INFO

Article history:
Received 19 November 2020
Received in revised form 28 January 2021
Accepted 14 February 2021

Keywords:
Fracture toughness
Self-compacting mortars
Waste glass
Fine aggregate
ENDB
Curing aging

ABSTRACT

The use of waste materials in the concrete industry has been a topic of interest for researchers around the world in recent decades. In this research, the fracture toughness (K_c) of edge-notched disc bend (ENDB) specimens of self-compacting mortars containing 0%, 20%, 40%, 60%, 80% and 100% waste glass aggregates (WG) under the pure mode 1, mixed mode 1/3, mixed mode 3/1, and pure mode 3 in ages of 14, 28 and 56 days have been studied. The results show that the use of 20% and 40% of WG will improve the fracture toughness of the mortars. On the other hand, increasing the curing age from 14 to 28 days, with and without WG, improves the fracture toughness of samples significantly. Increasing the curing age has the highest impact on the results of pure mode 3. In addition, due to the effective fracture toughness results, pure mode 3 is introduced as critical loading condition for self-compacting mortars containing WG.

1. Introduction

Concrete and its derivatives are used widely in the construction industry. The production of this large volume of concrete requires the continuous use of natural resources [1]. However, the continued use of natural resources and materials due to the exhaustion of natural aggregates, the negative effects of demolition, and the serious environmental controls on the construction process are limited. Therefore, introducing suitable alternative materials in this process can be helpful [2]. On the other hand, the increase in population and the expansion of cities, the significant progress of various industries, and the increase in the living standards have led to the production of large volumes of domestic and industrial waste materials. Isolation, treatment, and maintenance of this amount of waste materials are among the most discussed and important issues around the world. Hence, experts are looking forward to new strategies for using these materials [3]. Self-compaction will eliminate the noise and vibration problems and improve the concrete quality and flowability [4–7]. A basic step in the self-compacting concrete (SCC) design is to study the properties of self-compacting mortars because it well reflects the characteristics and performance of its related concrete [8]. According to Puthipad et al. [9], using air-entraining agent (AEA) in self-compacting mortars will prevent air bubbles coalescence after adding the superplasticizer. Using zeolite and nano-silica will not only affect the hydration process and pozzolanic activities positively, but also reduce the ion penetration in self-compacting mortars [10]. Safi et al. [11] showed that replacing 100% of the natural fine aggregates of self-compacting mortars with seashells will improve the flowability and slightly reduce the compressive strength.

Since ancient times, humans have used glass in various industries. Mainly, glass is produced in the form of bottles, containers,

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https://doi.org/10.1016/j.conbuildmat.2021.122711
0950-0618/Published by Elsevier Ltd.

windows, lamps, cathode ray tubes, etc. [12,13]. This large volume of glass production has increased the amount of waste glass too. On the other hand, in order to preserve the environment and prevent the increase of the depot space, the glass must be recycled, as it has been theoretically proven that glass is completely recyclable and the quality reduction does not occur in it [14]. However, due to the high cost of cleaning, separation, and color differentiation, only a small amount of waste glass is recycled [15]. Waste glass is widely used in the production of concrete (aggregates and cement), asphalt (aggregates), fillers (back-filling), sub-base, building blocks, tiles, artificial stones, and glass ceramics [16]. Many attempts have been made in recent years to use waste glass in the production of cement-based materials. Most of these efforts are focused on replacing all or part of the cement and aggregates in concrete and mortar with the waste glass [17]. Waste glass has been used as one of the most ideal materials to replace aggregates due to its special physical and chemical structure [18–23].

The low tensile strength of concrete plays an important role in the growth and development of cracks. The growth of cracks in concrete elements and reinforced concrete will accelerate the transfer of moisture, harmful gases, and ions, corrosion of rebars. The development of cracks will also increase the carbonation probability of hydration products, destruction of cement paste, and reduction of durability and life cycle of these materials. On the other hand, observing cracks in concrete elements and understanding its behavior is not easy and requires precise studies and monitoring [24]. To study the fracture parameters of different materials, use can be made of such methods as the size effect, work of fracture method, crack band method, effective crack method, two parameter model, cohesive crack method or fictitious crack method, double-G fracture method, KR-curve method, double-K fracture method, boundary effect method and simplified boundary effect method [25–40].

In addition, comprehensive understanding of failure mechanical parameters such as fracture toughness in mode 1 (opening or tension mode), mode 2 (sliding or in-plane shear mode), and mode 3 (tearing or anti-plane shear mode) leads to a better understanding of the growth and expansion of cracks in concrete [41,42]. Fracture toughness is generally defined as resistance to crack growth. Applying this parameter to determine the efficiency and behavior of different types of materials and composites during the design process and determining the service life of cracked materials by engineers, can be very useful [43,44]. Cracking mainly occurs due to the combination of loading modes. However, the failure phenomenon occurs in the pure state or combination of these modes [41,42]. The onset and growth of cracks in different parts of the structure are more common in the combination of mode 1–2 loading and 1–3 loading [45,46]. Therefore, the use of reliable, repeatable, comprehensive, and inexpensive methods with available equipment and easy configuration will be helpful in examining the fracture toughness parameter [43,47]. For this purpose, Aliha et al. [48] presented a new model called edge-notched disc bend (ENDB) to test and calculate the fracture toughness of composites such as asphalt and concrete. The loading process and sample preparation in this test are easier than other common methods of determining the amount of fracture toughness [43].

The use of glass powder as a substitute for cement in concrete or mortar and its positive effects on mechanical properties and durability, economic profitability, reduction of production costs, and reduction of environmental hazards have been reported by previous studies [49–56]. Besides, replacing the aggregates with waste glass increases the impenetrability and improves the durability of the concrete. This happens due to the acceleration of the pozzolanic reaction process and the reduction of cement paste cavities [57,58]. Afshinnia and Rangaraju [59] reported that the use of waste glass as fine aggregates in concrete has a negative effect on its mechanical properties. Concretes containing waste glass aggregates also have a higher ultrasonic pulse velocity [16]. The possibility of replacing all natural aggregates of architectural mortars with waste glass due to the inherent properties of glass aggregate such as impermeability, chemical resistance, cost reduction, and appearance has been shown in other studies [60,61]. Ling and Poon [2] claimed that there is no significant change in density until 40% of the cement-based mortar aggregates are replaced with fluorescent lamp glass, but the fluidity of concrete increases and its shrinkage decreases significantly. Guo et al. [62] concluded that at room temperature and temperatures below 800 °C, the use of waste glass as an aggregate in architectural mortars causes a slight reduction in electrical conductivity, compressive strength, and elastic modulus. However, as glass melts at 800 °C and fills the cavities of cement paste, the growth of cracks decreases and the mechanical properties will improve.

Choi et al. [63] claimed that it is possible to use the waste glass as aggregate in cement mortar as their studies showed that it reduces the shrinkage of concrete despite a slight increase in ASR value. Tan and Du [64] stated that the use of 0%, 25%, 50%, 75%, and 100% waste glass as mortar aggregates increases the amount of air content at fresh phase and resistance to chloride ion penetration. However, the presence of cracks in the waste glass grains and the weak connection of the cement paste with the glass grains will reduce the mechanical parameters. They concluded that transparent glass has a higher ASR potential than the green and brown glass. The different performance of waste glass aggregates in cement-based materials has been reported depending on the particle size, including negative performance due to alkali-silica reaction and positive performance due to pozzolanic reaction [65]. Another study reported that the use of fine waste glass particles will increase the initial and final setting time of concrete setting [66]. Thus, the setting of mortars containing waste glass can be evaluated by examining the effects of curing age.

Zhang et al. [35] have reported that using polypropylene fibers will increase the strength of the cement treated crushed rock against the crack growth by up to 0.1%. Kumar et al. [36] believe

Table 1
Properties of type II Portland cement of Sistan Cement Factory.

Chemical properties (%)	Results	Physical properties	Results
SiO_2	21.05	Specific surface area (cm^2/g)	3110
Al_2O_3	4.76	Setting time (initial) (min)	183
Fe_2O_3	3.43	Setting time (final) (min)	238
CaO	62.86	Autoclave Expansion (%)	0.08
MgO	3.46	Compressive strength(3 Days) (kg/cm^2)	265
Na2O	0.21	Compressive strength(5 Days) (kg/cm^2)	451

Table 2
Properties of mortar aggregates.

Sieve size (mm)	Natural fine aggregate (%passing)	Waste glass aggregate (%passing)
4.75	100	100
2.36	77.2	64.7
1.18	59.5	38.9
0.6	37.1	19.3
0.3	24.8	10.7
0.15	8.4	4.6
Relative density (g/cm^3)	2.68	2.42
Water absorption (%)	1.14	0.24

Fig. 1. WG aggregates used in this study.

Table 3
Properties of super-plasticizer.

Properties	Testing results	
Density (20 °C)	1.11	According to ASTM C494
PH (20 °C)	6.94	
Chlorine (ppm)	975	
Color	Brown	

that since most existing conventional experimental/analytical methods require the crack opening displacement at critical conditions to determine the fracture parameters, the peak load method can (nearly) accurately find both fracture parameters of the double-K method. In the cohesive crack model, the fracture energy, defined in the work-of-fracture method, as the work done to create a unit crack area, is very important and can be calculated by measuring the area under the load–displacement curve [67]. However, the initial fracture energy (in the size effect model) is the men-

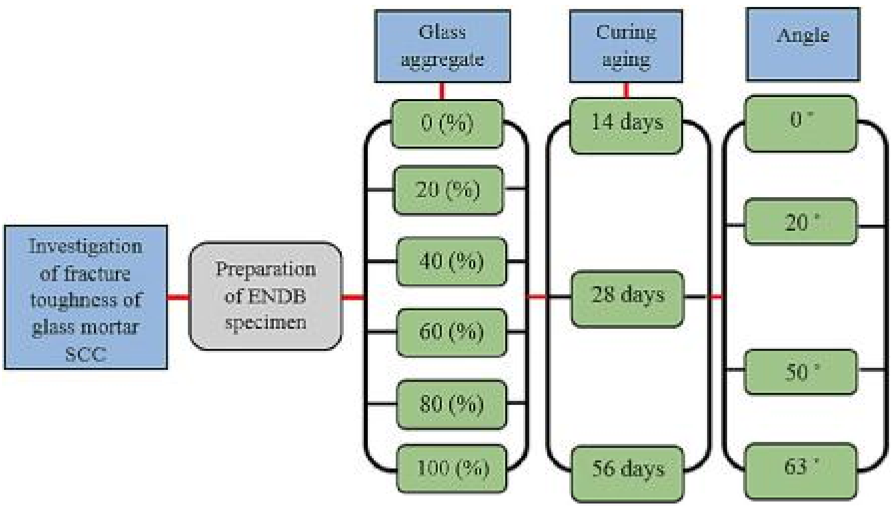

Fig. 2. Flowchart of design experiment in this research.

Table 5
Mixing procedure of mortars.

Procedures	Time (s)
1. Add of natural and waste glass aggregates.	60
2. Add of water (50%).	30
3. Add of cement.	60
4. Add of water (50%) and super-plasticizer.	60
5. Final mix	90

tioned area before the maximum load and does not depend on the specimen geometry and size [68].

ENDB samples have been used to investigate the characteristics and failure parameters of different materials and composites under the influence of pure mode 1, pure mode 3, and the combination of these two modes in the former studies [69,70]. Golewski and Sadowski [71] stated that the use of 20% fly ash would cause a slight improvement in K_{3c}. However, they concluded that adding 30% of fly ash reduces the fracture toughness. However, when the curing time of specimens containing 30% fly ash is>180 days, the fracture toughness will increase significantly [72]. Linear and nonlinear parameters of the fracture mechanics and the behavior of concretes containing such cement substitutes as the fly ash under different loading modes depend on the pozzolanic activity [73]. Safari et al. [74] showed that using rice husk ash will improve the fiber-cement paste bond and transfer loads well from fibers to the matrix. They believed that this mechanism had positive effects on the fracture energy absorption process when micro-cracks propagate.

Aliha et al., [75] examined the effects of Forta fibers on the fracture characteristics of concrete using ENDB samples. The results showed that the addition of these types of fibers will significantly increase the fracture toughness and fracture energy. On the other hand, they observed that when $K_{1c} > K_{3c}$, the fracture energy in mode three is higher than in mode one. Mansourian et al. [76] replaced the fine and coarse aggregates of concrete with the asphalt recycled aggregates and evaluate the fracture toughness of this type of concrete in pure mode 1, pure mode 3 and combined (1/3 or 3/1) modes under the temperatures of −25 °C, 0 °C, and + 25 °C using ENDB samples. Their investigations showed that the use of recycled asphalt aggregates reduces the fracture toughness of concrete in different modes. However, for the lower temperatures, higher values of fracture toughness were reported for the concretes containing asphalt recycled aggregates.

The reduction of strength and gradual deterioration of concrete depends on the initial defect, internal structure, and the applied loads. The characteristics and size of the aggregates also have a great impact on the performance of cement-based composites in

Table 4
Mortar mixtures properties.

Component	WG0	WG20	WG40	WG60	WG80	WG100
Cement (kg/m^3)	700	700	700	700	700	700
Natural fine aggregate(kg/m^3)	1400	1120	840	560	280	0
Waste glass fine aggregate(kg/m^3)	0	280	560	840	1120	1400
Water to cement ratio (%)	0.45	0.45	0.45	0.45	0.45	0.45
Super-Plasticizer (%)	4.5	4.2	3.6	2.5	1.6	1

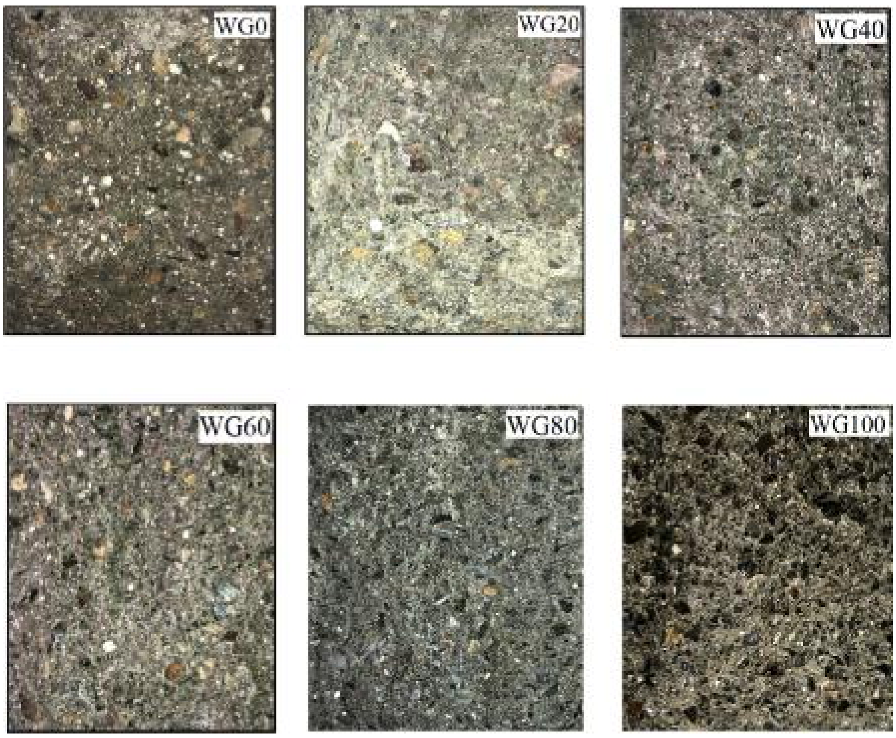

Fig. 3. Mini slump test of different mortars with and without WG.

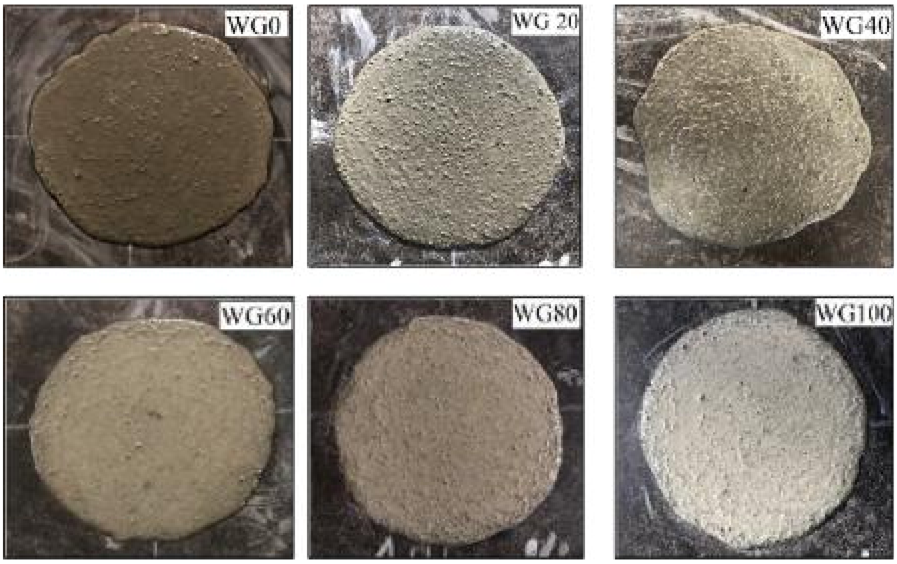

Fig. 4. Different specimens' mortars with and without WG.

the failure process [71,77,78]. The effect of using waste glass as aggregate on the mechanical properties and durability of concrete, mortar, and cement-based materials has been studied in detail in former studies [12–16]. In addition, most of these studies have

Fig. 5. Prepared specimens' mortars with and without WG.

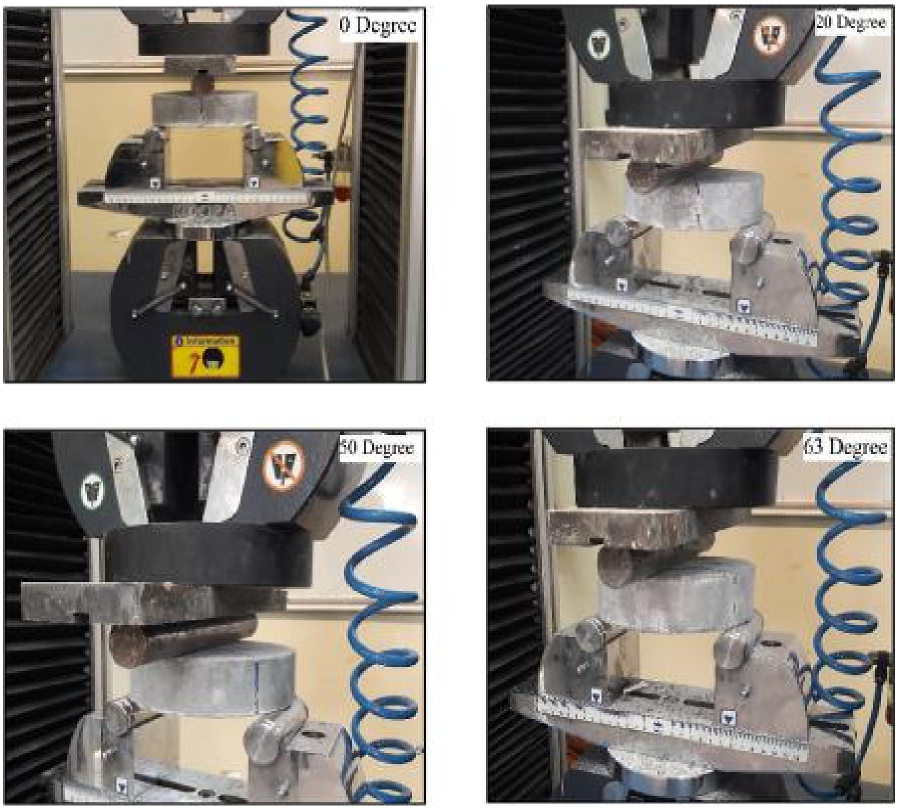

Fig. 6. ENDB samples under different pure and mixed modes (1, 1/3, 3/1 and 3).

tested the desired parameters at the 28-day curing age. However, no comprehensive research has been conducted to evaluate the effect of curing age and replacement of natural concrete or mortar aggregates with waste glass on fracture parameters, especially fracture toughness in different loading modes. Determining the fracture toughness parameter and behavior of different materials such as concrete or mortar, under pure and mixed loading modes, using ENDB specimens that have simple geometry and are easy to prepare and test, has several applications (e.g. studying properties of engineering material, determining proper retrofitting methods, optimizing and increasing the design process accuracy, producing concrete structures, preparing codes etc.). Therefore, in this study, the effect of replacing 0%, 20%, 40%, 60%, 80% and 100% of self-compacting mortar aggregates with waste glass and curing age of 14, 28 and 56 days on the fracture toughness of pure mode 1, pure mode 3, and the combination of these two modes have been investigated using ENDB.

2. Experimental study

2.1. Material properties

The type-II cement has been used in this study. The specifications of this cement are presented in Table 1 accordance with ASTM C150 [79] regulations. Natural fine aggregates with a maximum size of 4.75 mm and physical characteristics according to Table 2 have been used in samples. The percentage of passage through each sieve for the waste glass aggregates used in this study is also shown in Table 2.

The waste glass materials used in this study were made from unused bottles collected from the supermarkets. The collected bottles are separated, washed, and cleaned in the first step. Next, the bottles were crushed. The waste glass is then classified and sieved. Fig. 1 shows the steps of collecting, cleaning, crushing, and classification of waste glass. Table 2 presents the physical properties and granulation of waste glass. Drinking water as per ASTM C94 [80]

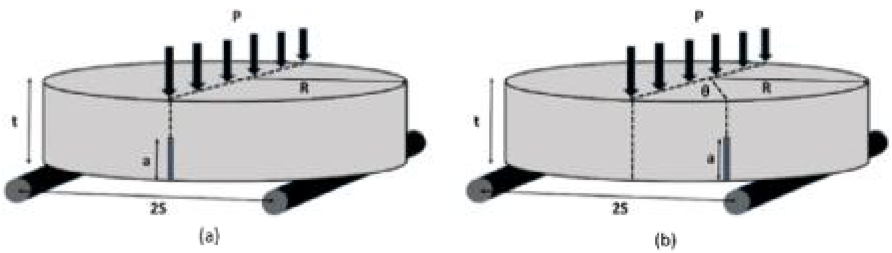

Fig. 7. Geometry specification and loading setup in ENDB samples [87].

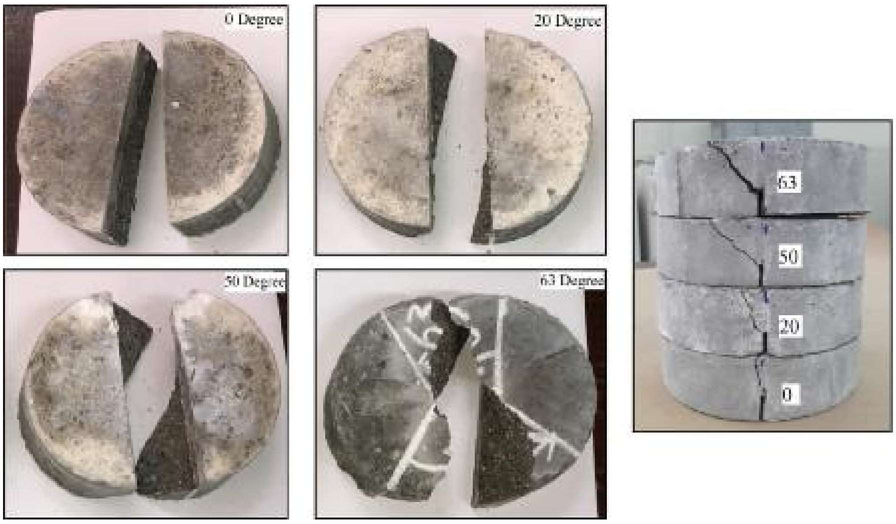

Fig. 8. Fracture paths of ENDB samples under different pure and mixed modes (1, 1/3, 3/1 and 3).

has been used to produce self-compacting mortar. To produce mortar samples with optimal performance, a water-reducing admixture based on poly-carboxylate ether, RB-PC 375, in accordance with ASTM C494 [81] has been used (Table 3).

2.2. Mix proportions

To evaluate and calculate the fracture toughness, natural aggregates of self-compacting mortar were replaced with 0%, 20%, 40%, 60%, 80%, and 100% waste glass and ENDB samples were tested at 14, 28, 56 days of age (Fig. 2). Thereupon, a total of 6 mortar mixtures named as WG0 (control mixture), WG20, WG40, WG60, WG80, and WG100 containing 20% to 100% waste glass have been designed. The design specifications of mix designs with and without waste glass are given in Table 4. Due to the large volume of powder used in the production of self-compacting mortar and to provide a high volume fraction of fine materials the amount of cement used is equal to 700 kg/m^3 and the ratio of cement-based materials to fine aggregates is 1: 2 [82]. The ratio of water to cement (W/C) is equal to a constant value of 0.45. To provide the slump and proving the self-compactness of the concrete, a super plasticizer admixture was added in such a way that the amount of mini-slump in the mortar was in the range of 240 ± 20 mm. The steps and duration of mixing the materials are presented in Table 5.

2.3. Mini-slump flow and compressive strength test

Here, the workability and slump of the self-compacting mortars containing waste glass have been evaluated according to EFNARC [83] using a mini-slump cone. After completing the process of mixing and producing the self-compacting mortar with the desired specifications, the mini-slump cone is placed on a flat plate and filled with mortar (without any compaction). Then the mini-slump rises vertically and the average diameters perpendicular to the spread concrete will be reported as the final slump number. Fig. 3 shows the mini-slump test of different mixing designs. According to BS 1881: Part 116 [84], after performing fresh mortar tests, a 100 mm cube sample was filled without vibration at the ages of 14, 28, and 56 days for each mixing design and the compressive strengths were evaluated. Fig. 4 shows the sample surface using different percentages of WG to make self-compacting mortar in the hardening phase.

2.4. Preparation of ENDB specimens and fracture toughness test

In previous research, the use of ENDB to determine the fracture toughness in pure mode 1 or pure mode 3 modes and the combination of these two modes has been reported as a useful and easy method [18]. Samples of ENDBs are circular disks with D diameter

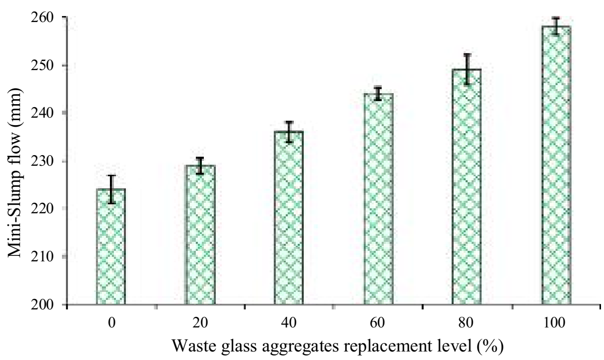

Fig. 9. Effect of WG on mini slump of mortar mixtures.

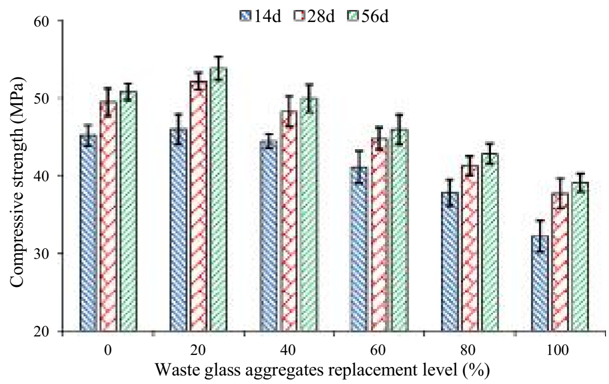

Fig. 10. Effect of WG on compressive strength test of mortar mixtures.

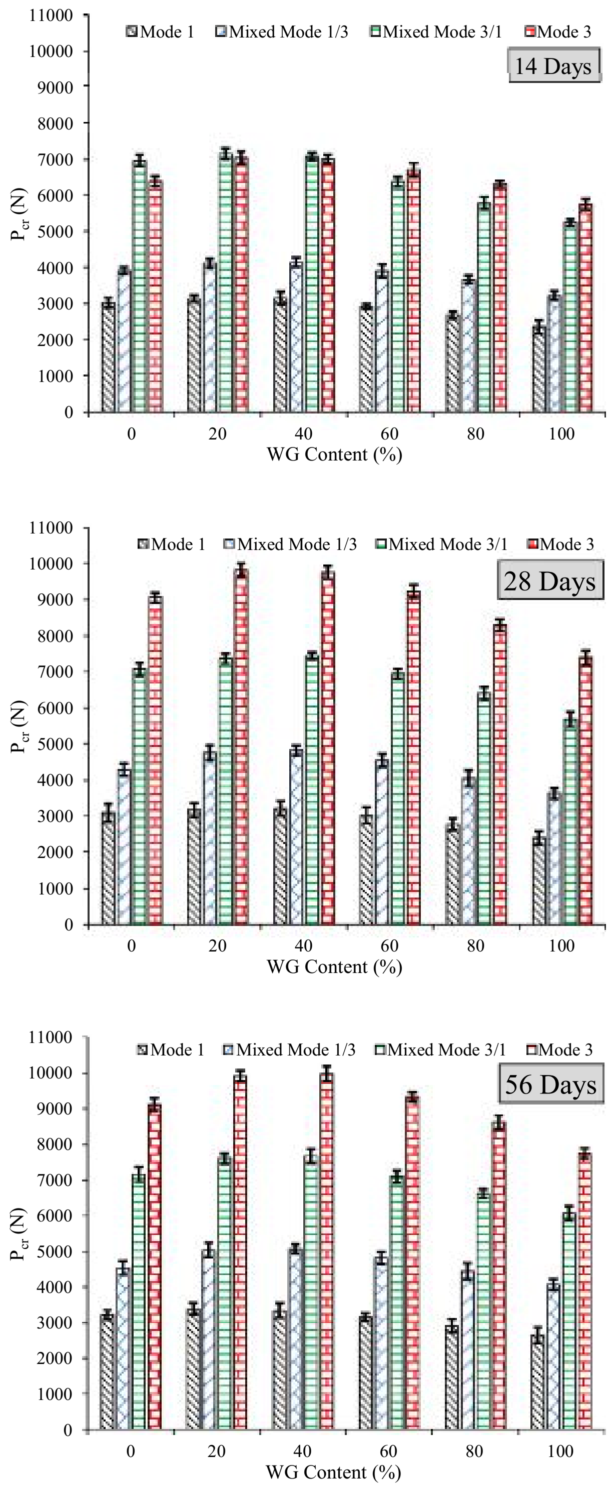

Fig. 11. P_{cr} of mortar mixtures.

(R radius) and t height. On one side of the surface of these specimens and in the direction of their diameter, a crack is created to a depth of a. To this end, molds were prepared with the desired specifications, and a thin plate was used to create the initial crack (Fig. 5).

To achieve the pure mode 1, pure mode 3, and the combination of these two modes, the deviation angle of the crack (θ) and the direction of the applied load should be equal to 0, 60 to 65 and 0 to 60°, respectively [85,86]. Fracture toughness parameter (critical value of stress intensity factor) of pure 1 (K_{1C}) and pure 3 (K_{3C}) modes and the effective stress intensity factor parameters (K_{ef}) of ENDB samples are calculated using eqs. (1) to (3):

$$K_{1C} = \frac{6P_{cr}S}{Rt^2}\sqrt{\pi a}Y_1 \quad (1)$$

$$K_{3C} = \frac{6P_{cr}S}{Rt^2}\sqrt{\pi a}Y_3 \quad (2)$$

$$K_{ef} = \sqrt{(K_{1C})^2 + (K_{3C})^2} \quad (3)$$

P_{cr}, a, 2R, and 2S are the applied failure load, the initial crack height, the disk-shaped sample diameter (150 mm), and the distance between the bearing axes (142.5 mm), respectively. t is the sample thickness (40 mm). Y_1 and Y_3 are the pure mode 1 and pure mode 3 geometric coefficients, respectively (selected according to reference [48]).

Determining the share of each of mode in different θ values will help to understand the mixed mode loading conditions comprehensively. When pure-1 and pure-3 modes occur, the values of the M^e_{13} mixity parameters are equal to 1 and 0, respectively. But in the case of combination of modes 1 and 3, the M^e_{13} value will be between 0 and 1 (Eq. (4)).

$$M^e_{13} = \frac{2}{\pi}Tan^{-1}\left(\frac{K_{1C}}{K_{3C}}\right) \quad (4)$$

In this research, the dimension and geometry of the samples, loading rate and the performing method have been selected based on reference [18]. After preparing ENDB samples, the universal TB-50 T device were used with a constant loading rate of 2 mm/min for load application. Since these tests were displacement-controlled, use was made of a closed-loop servo electro controlled testing universal machine, but, first holding the accessories by hand, the device jaw neared the specimen close enough fully tangent to the loading location. No motion or change occurred in the loading location because the loading rate was low and accessories were trapped between the jaw and the specimen. Load-displacement diagrams are recorded for all samples with WG replacement percentages of 0 to 100 and different crack deflection angles (0, 20, 50 and 63°), at the ages of 14, 28 and 56 days until the failure. Fig. 6 shows the loading conditions under different modes.

3. Experimental results and discussions

Fig. 7 shows the test set-up to investigate the fracture toughness of WG-containing samples in the pure mode 1, pure mode 3, and the combination of these two modes. The pattern direction of the failure for ENDB specimens under different loading conditions are shown in Fig. 8. According to Fig. 8, with increasing the load deviation angle from 0 to 63°, the rotation of failure direction and pattern, relative to the initial crack, are quite evident in all samples.

3.1. Mini-slump test

The results of the mini-slump test of mortars containing 0% to 100% WG are shown in Fig. 9. According to Fig. 9, the amount of mini-slump of all mortars is in the range of 220 to 260 mm. In general, replacing natural aggregates with waste glass has improved the properties of fresh mortar and reduced the amount of needed

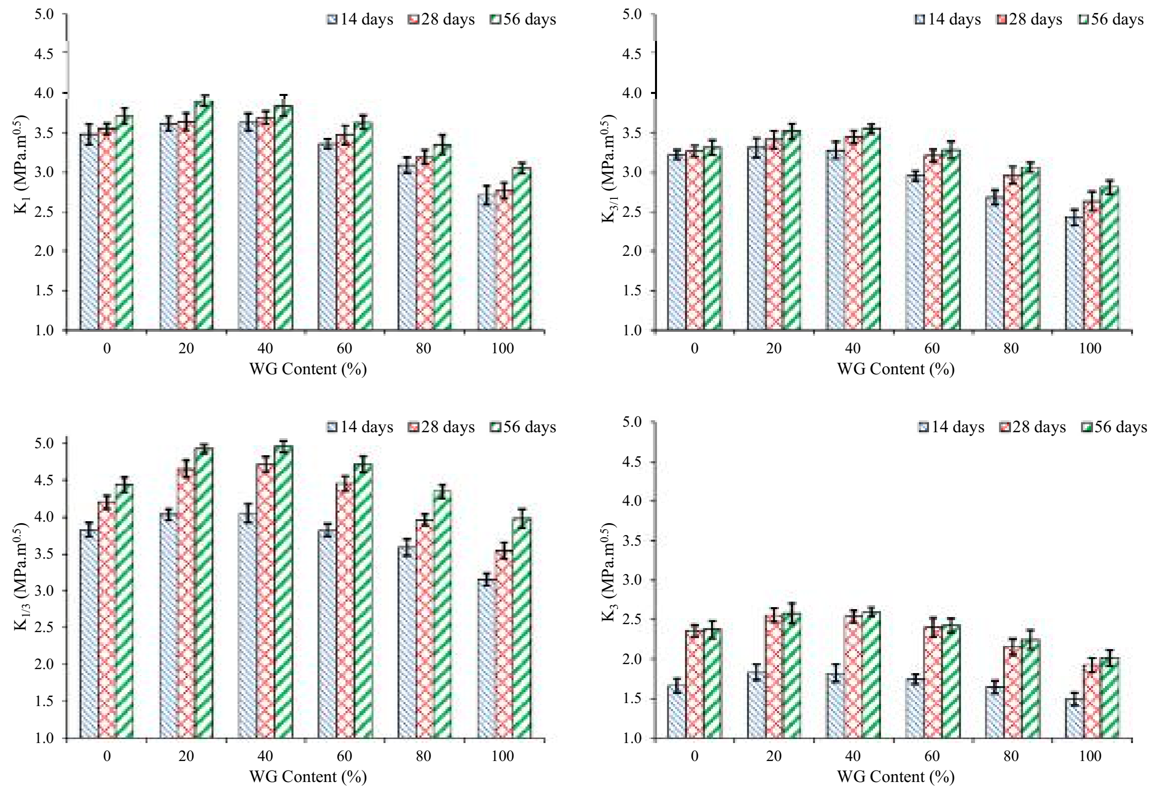

Fig. 12. Fracture toughness of the mortar mixtures.

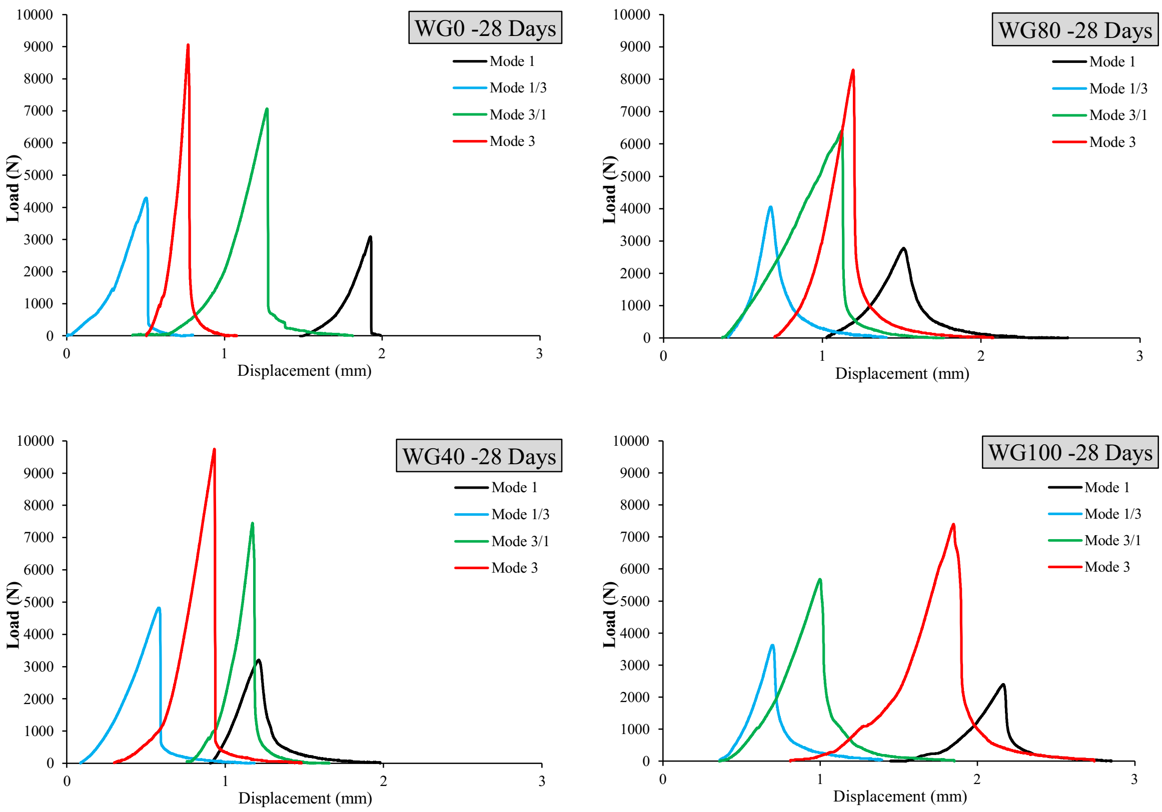

Fig. 13. Load-displacement curves of mortar mixtures.

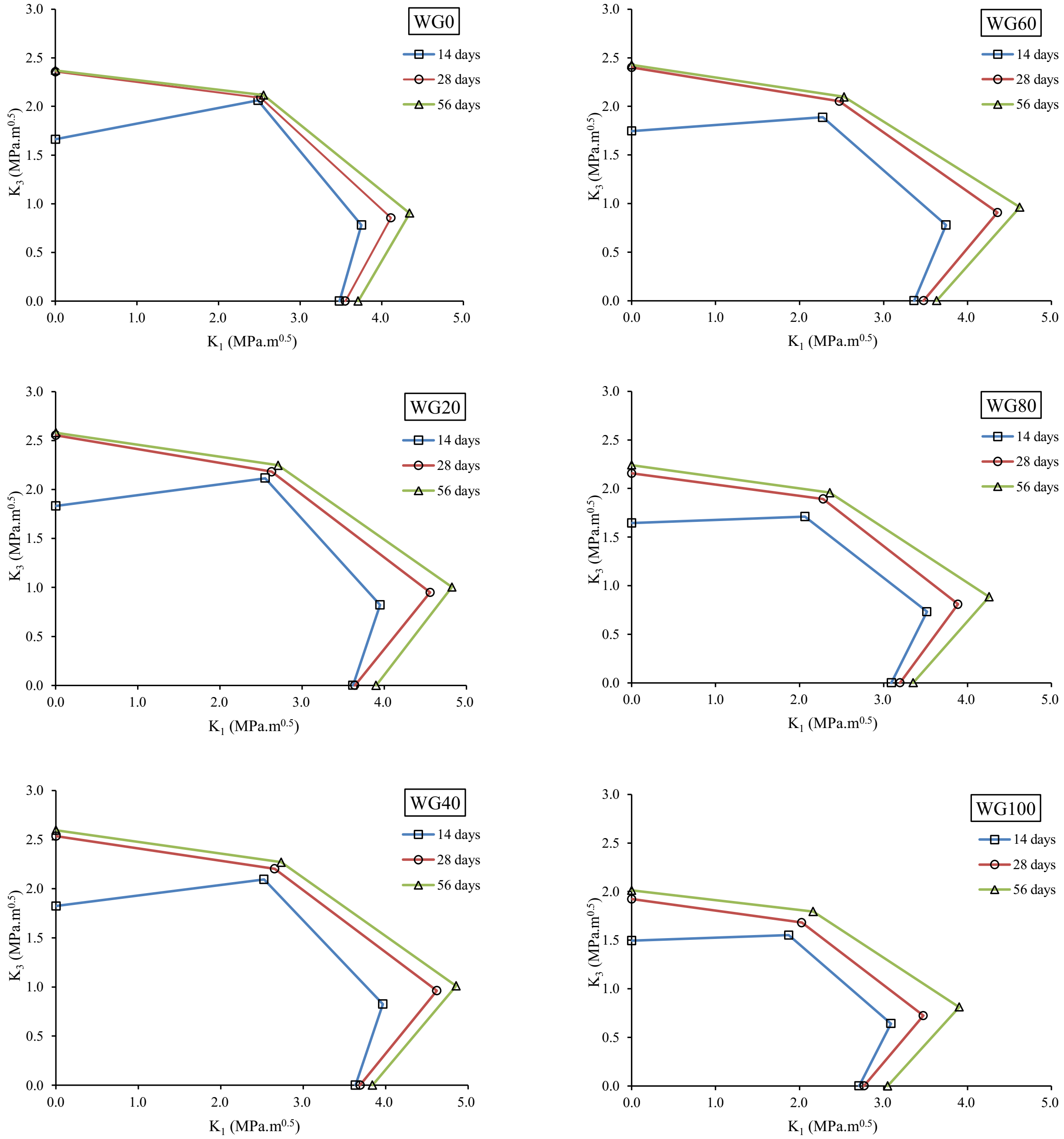

Fig. 14. Effect of age curing and waste glass on fracture toughness of the mortar mixtures.

super-plasticizer. The positive effect of using WG as aggregate in mortar production is due to the smooth surface of aggregates and their very low water absorption [82]. Although a similar trend has been reported by Nawaz Khan et al. [88] for the mortar workability using waste glass aggregates, the fineness modulus of the latter causes the fresh concrete/mortar containing this material to perform differently [89,90].

3.2. Compressive strength test

Fig. 10 shows the compressive strength of mortars with and without WG at different ages. The compressive strength of different samples are in the range of 32.2 to 46, 37.7 to 52.2 and 39.1 to 53.9 MPa, at the ages of 14, 28 and 56 days, respectively. Replacing natural aggregates with 20% WG has improved the compressive strength of samples at different ages. At the ages of 14, 28 and 56, the WG20 design showed a 1.77%, 5.46% and 5.96% increase in compressive strength compared to WG0, respectively. Improving the strength at this percentage of replacement can be due to angularity of glass grains and the increase in their bonding to the cement paste, which occurs due to the expansion of the interfacial transition zone (ITZ) [91,92]. Using such cement additives as nano-silica and nano-clay in mortars containing the waste glass improves the long- and short-term strengths, respectively [93]. The WG40 design showed a slight decrease at different ages compared to WG0 (<3%). WG100 at the ages of 14, 28 and 56 days had

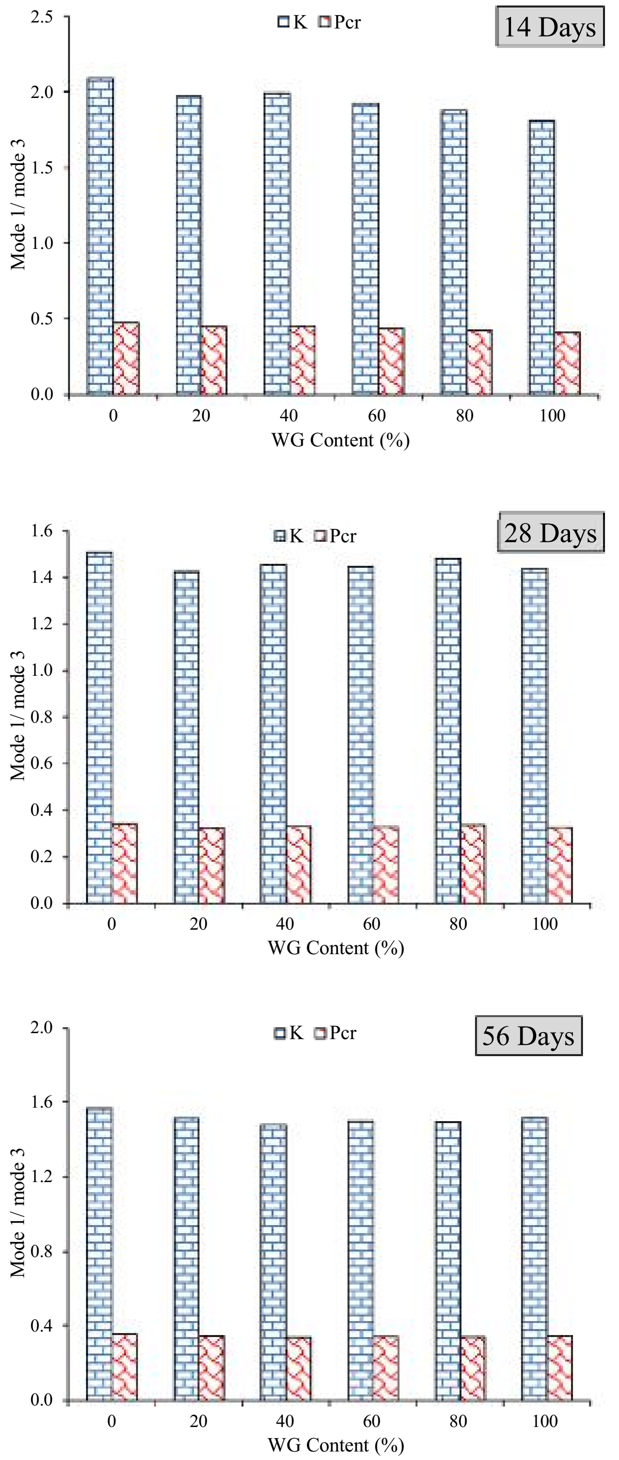

Fig. 15. Comparison of mode 1 and mode 3 fracture parameter results of mortar mixtures.

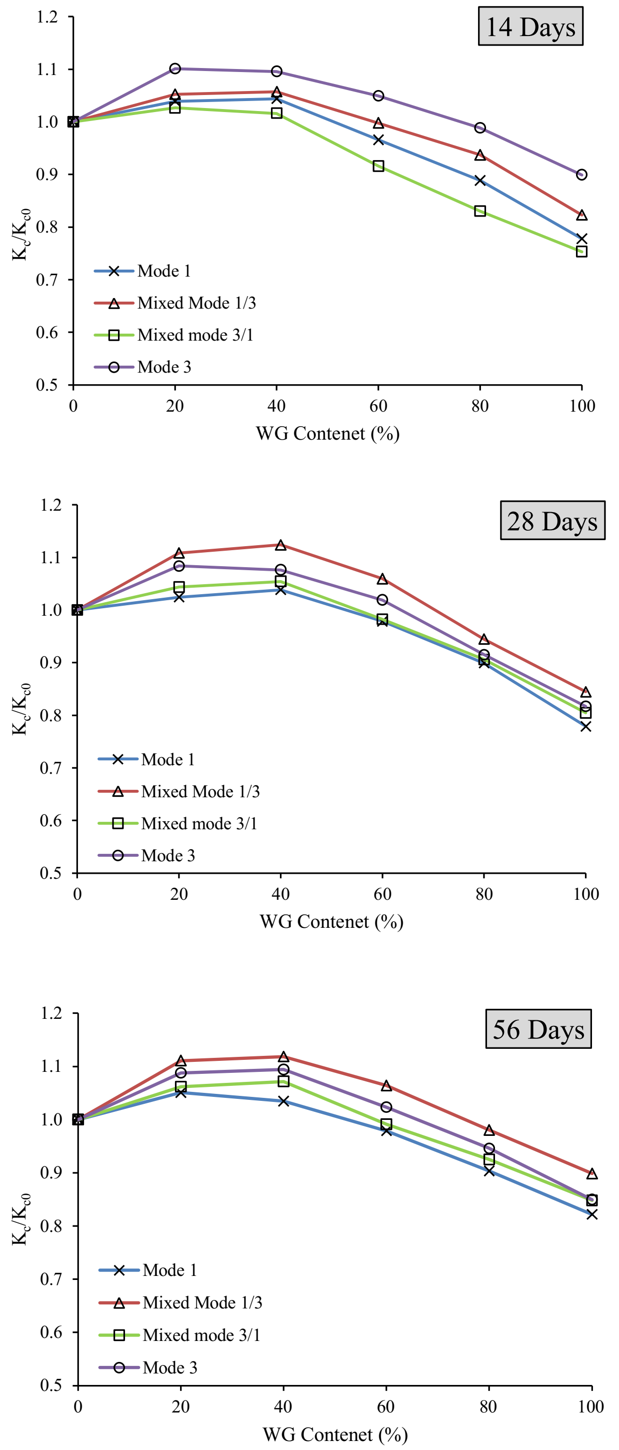

Fig. 16. Comparison of normalized fracture toughness ratio (K_c/K_{c0}).

34.95%, 23.84% and 21.05% reduction of compressive strength, respectively. Previous researches have reported that when specimens containing the waste glass gain age, the difference in their compressive strength is reduced [88]. The reduction in compressive strength in samples containing WG (40%, 60%, 80% and 100%) is a result of low resistance and existence of micro-cracks in these WG aggregates as well as their poor bonding with the cement paste because of the stepped fractures [40,94].

3.3. Effect of waste glass

The critical load variations of samples with and without WG for different loading modes are shown in Fig. 11. As shown, mainly the lowest and highest P_{cr} values occur in pure mode 1 and pure mode 3, respectively. The replacement percentages of 20 and 40 have higher critical loads than the control mix design in different loading modes. At higher percentages, a significant decrease in P_{cr} of the samples is observed. At 14 days of age alone, at 0%, 20%, and 40% replacement percentage, the P_{cr} of the 3/1 combined mode is higher than the pure-3 mode. However, with increasing the replacement percentage (>40%), the amount of P_{cr} in pure-3 will be higher than other loading modes. Using 60%, 80% and 100% of WG as aggregates in the mortar will reduce the fracture toughness (Fig. 12). The greatest decrease in fracture toughness has been observed for the 1/3 combined load mode at 28 and 56 days. There was a significant difference between the fracture toughness of samples with and without WG in pure mode 3 and 1/3 combined mode at the ages of 14, 28 and 56 days. The load–displacement curves of the mix designs containing 0%, 40%, 80%, and 100% WG are shown in Fig. 13 (28 days). Under all load modes, the WG0 has experienced a sudden drop after the maximum load. However, WG-containing designs experience a nonlinear (gradual) load drop after reaching peak load and undergo more displacement until total failure. This merit enables the use of these glass-containing composites as suitable construction materials to reduce the damage caused by dynamic loads and earthquakes. Increasing the percentage of WG increases the displacement during the load application and increases the bearing capacity in the descending line of the load–displacement diagram. According to Fig. 8, in pure mode 1, specimens are divided into two equal parts, but an increase in crack angle θ and the loading mode tending toward pure mode 3, causes a twist in the specimen failure relative to the initial crack plane.

3.4. Effect of curing aging

Studying the performance effects of different-age cementitious composites is quite important, especially for such large structures as dams, tunnels, foundations, nuclear structures and so on to ensure their durability and serviceability at early ages [95]. The changes in fracture toughness against the percentage of WG replacement at different ages are shown in Fig. 12. Increasing the curing age (14 to 56 days) has the greatest effect on the amount of fracture toughness in pure mode 1/3. Changes in fracture toughness at high replacement percentages (60, 80, and 100) are more evident under all loading modes compared to the low percentages (0, 20, and 40). The reason for this phenomenon can be attributed to the intense decrease in strength at high replacement percentages. Fracture toughness varies slightly with increasing the curing age from 28 to 56 days. Golewski [96] has shown that the critical stress intensity factor K_{3c} depends on the concrete age, and other researchers [97-99] have reported that an increase in age will increase the fracture energy and fracture toughness of cementitious composites. Fig. 14 shows the safe zone of mortars containing WG at different ages for applied loading modes. According to Fig. 14, the trend and form of changes in these diagrams are similar in 0 to 100 percentages of WG and clearly show the effects of aging on mortars containing different percentages of glass. The WG20 and WG40 have a larger safe area than the control mixture. These diagrams can be used in the design process of structures and elements.

3.5. Effect of loading modes

The aggregate-mortar interaction and heterogeneity of concrete derivatives cause three cracking models (1–3) to occur under external loads [100]. A comparison of the results of the fracture toughness (K_C) and critical load (P_{cr}) parameters for pure mode 1 and pure mode 3 are presented in Fig. 15. At all ages and replacement percentages, the fracture toughness of pure mode 1 is about 1.4 to 2.1 times the fracture toughness of pure mode 3. At the age of 14 days, there is a greater difference between the fracture toughness of pure mode 1 and pure mode 3. According to Fig. 15, the failure load in pure mode 1 is approximately 0.3 to 0.5 times the failure load of the pure mode 3. This indicates that the failure propagation phase in pure mode 3 requires more energy than pure mode 1 [47]. Pure mode 3 conditions are observed in pipes, shafts, cylinders subject to torsion, pavements of roads under traffic, earth crust sliding during earthquakes, and so on [44]. Therefore, it can be said that the type of loading applied to samples with and without WG has a great impact on their failure mechanism and damage behavior.

For better comparison at 14, 28, and 56 days of age, the fracture toughness of different loading modes has been normalized to the results of the control design (Fig. 16). Fig. 16 shows that the use of low percentages of WG in the mortar will increase the fracture toughness by 5% to 12% compared to the control mixture under different loading modes. At the age of 14 days, most changes occur in pure mode 3. However, with increasing the curing time (28 and 56 days), the 1/3 combined mode shows more changes than the other modes. Aliha et al. [46] have reported, after normalization of the fracture toughness and fracture energy, that fibers generally increase the load bearing capacity of cementitious mixes. The range of fracture toughness changes (the difference between the minimum and maximum values) of mortars containing 0% to 100% WG is shown in Fig. 17. Pure mode 1 and pure mode 3 have the highest and lowest range of changes, respectively, at the ages of 14 days (Fig. 17). But, the 1/3 combined mode has more amount than the other modes at 28 and 56 days. In addition, according to the results, with an increase in the curing age (56 days), the range of changes has decreased significantly.

Effective fracture toughness changes and mixity parameters of all mortars with and without WG at different ages and loading modes are shown in Fig. 18. Due to the lower amount of effective fracture toughness of all samples in pure mode 3, this mode is introduced as the critical mode. Because the risk of cracking or brittle fracture in mortars (with and without waste glass) subjected to pure mode 3 (out-of-plane deformations) is much higher than other loading modes [56].

According to Fig. 18, the reduction of effective fracture toughness of WG0 in pure mode 3 compared to pure mode 1, at the ages of 14, 28 and 56 days are equal to 52.2%, 33.7%, and 36.1%, respectively. The amount of effective fracture toughness reduction of the samples containing WG at the ages of 14, 28, and 56 days is in the ranges of 44–49, 29–32, and 32–34 percent, respectively. Examining the effective fracture toughness of concretes made with

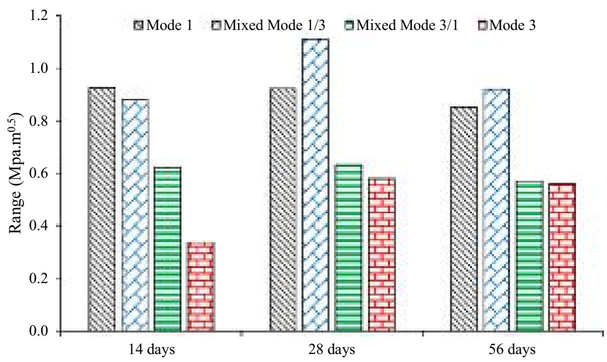

Fig. 17. The range of the fracture toughness of mortar mixtures.

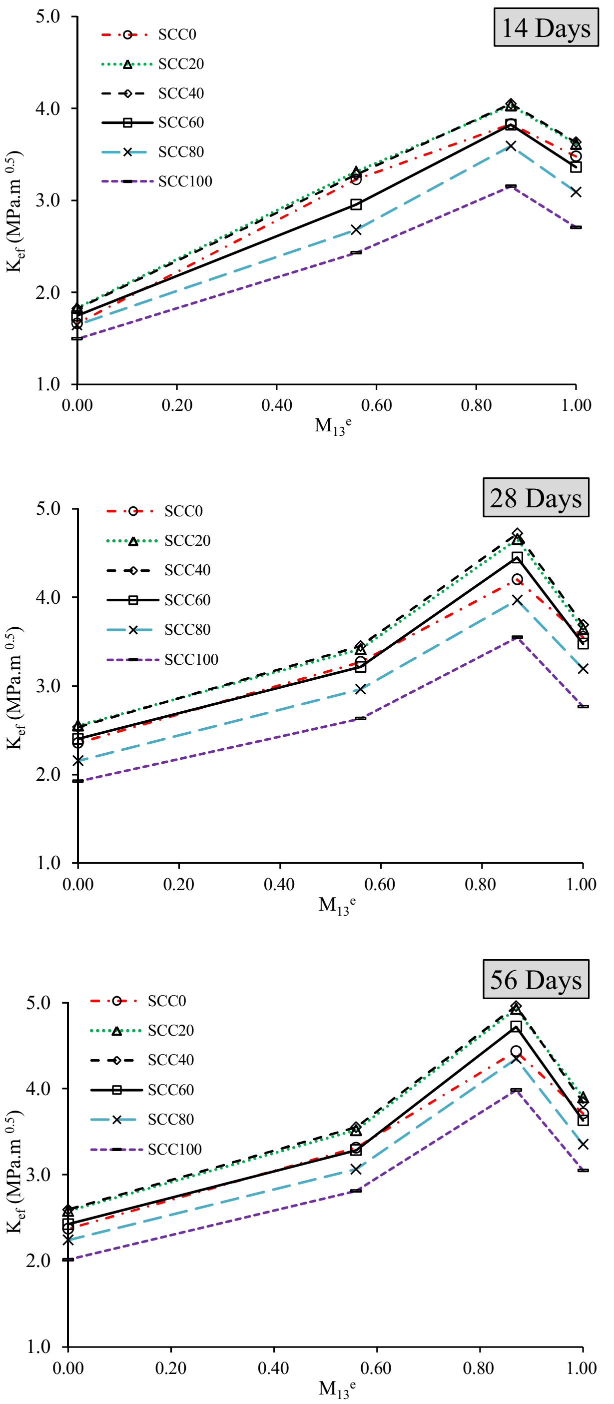

Fig. 18. Variations of K_{ef} versus M^e for the mortar mixtures.

reclaimed asphalt pavement materials, Mansourian et al. [42] concluded that their behavior is more critical in pure mode 3.

4. Conclusions

In this study, the effect of using waste glass (0%, 20%, 40%, 60%, 80%, and 100%) and the curing age (14, 28 and 56 days) on the fracture toughness of pure mode 1, mixed mode 1/3, mixed mode 3/1, and pure mode 3 of self-compacting mortars have been investigated and the followings were obtained:

1. Despite negative effects of using high percentages of glass waste replacements (>20%) on the compressive strength of self-compacting mortars, those containing 20 and 40% glass show improvements in the fracture toughness and critical load.
2. The K_{3c} of each mortar is highly reduced compared to its corresponding K_{1c}, but the tearing modes of mortars with and without waste glass require more fracture load and work than tensile modes.
3. In general, an increase in the curing age increases the fracture toughness; however, the mortar behavior under out-of-plane shear loading conditions (pure mode 3) is more dependent on the curing age than other modes and the curing age effect is more prominent in high replacement percentages.
4. Samples containing WG have less effective fracture toughness reduction at different ages than the control mixture. According to the results of effective fracture toughness of all mixing designs, the pure mode 3 is introduced as the critical loading condition.

CrediT authorship contribution statement

Seyed Roohollah Mousavi: Conceptualization, Methodology, Investigation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Iman Afshoon:** Resources, Writing - original draft, Data curation, Software. **Mohammad Ali Bayatpour:** Writing - original draft, Software. **Amirhossein Davarpanah T.Q.** Writing - original draft, Software. **Mahmoud Miri:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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