



Drop-Weight Impact Tests on Engineered Cementitious Composites heated to 500 °C

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Abstract

Despite that concrete is a fire-resisting construction material, its microstructure suffers significant chemical and physical changes when subjected to temperatures higher than 400 °C. Therefore, the combined effect of unexpected impacts and fire can lead to the collapse of the structure. To evaluate this combined effect, an experimental program was directed in this study using the ACI 544-2R repeated impact test method. Shallow cylindrical specimens with 150 mm diameter and 64 mm depth were prepared to evaluate the cracking and failure impact strengths of normal strength concrete (NC) and engineered cementitious composites (ECC). The ECC mixture was reinforced with 2% of polypropylene fibers. In addition to the impact strength, the compressive and flexural strengths of NC and ECC mixtures were also investigated. The impact, compressive and flexural tests were performed on unheated specimens and others heated to 500 °C to evaluate the residual strengths of NC and ECC mixtures. The results showed that before heating, ECC exhibited a failure impact performance that is approximately 6 times more ductile than that of NC, where the retained failure impact numbers of NC and ECC were 57 and 259 blows, respectively. However, both mixtures lost approximately 95% of their impact strengths after exposure to 500 °C.

Keywords: ECC; repeated impact; drop-weight; high temperatures; impact ductility

الخلاصة:

بالرغم من أن الخرسانة تعتبر مادة بناء مقاومة للحريق، إلا أنها تتأثر بشدة بتغيرات فيزيائية و كيميائية عند تعرضها الى درجات حرارة أعلى من 400 درجة مئوية، لذا قد يقود التأثير المشترك للحريق وأحمال الصدمة الغير متوقعة الى انهيار المنشأ. لتقييم هذا التأثير المشترك، تم توجيه برنامج مختبري في هذه الدراسة باستخدام فحص حمل الصدمة المتكرر الموصى به مدونة معهد الخرسانة الأمريكي رقم 544-2R (ACI) حيث تم استخدام نماذج اسطوانية ضحلة بقطر 150 ملم وسمك 64 ملم لتقييم مقاومة حمل الصدمة في حالة التشقق وحالة الفشل لخرسانة ذات مقاومة اعتيادية (NC) و مركبات اسمنتية هندسية (ECC) تحتوي على 2% من اليف البولي بروبيلين. بالإضافة الى فحص حمل الصدمة فقد تم فحص مقاومة الانضغاط ومقاومة الانثناء لكلا الخليطين الخرسانتين حيث أجريت الفحوص لنماذج غير مسخنة وأخرى مسخنة الى 500 درجة مئوية. بينت النتائج أن المركبات الاسمنتية الهندسية عند الفشل أظهرت تصرفاً أكثر مطيلية بستة أضعاف مقارنة بالخرسانة ذات المقاومة الاعتيادية حيث فشلت الأولى بعد 259 طرقة بينما فشلت الثانية بعد 57 طرقة فقط إلا أن كلا الخليطين فقدتا ما يقارب 95% من مقاومتها الأصلية لأحمال الصدمة بعد التسخين الى 500 درجة مئوية.

1. INTRODUCTION

Concrete is a good fire resisting material when compared with other construction materials like timber or steel. However, high temperatures would negatively impact the strength, structural performance and durability of concrete and reinforced concrete members. Early research works revealed that the degree of compressive strength degradation depends mainly on the test type and aggregate type [1, 2]. Other researchers reported different behaviors for normal strength and high strength concretes exposed to high temperatures [3-6]. When a concrete specimen is subjected to gradual increase of temperature, it exhibits a series of different strength-temperature behaviors, which depend on the applied stresses in addition to the heating regime and material constituents. For instance, many previous works reported different behaviors for compressive strength and tensile strength tests [7-9]. However, the temperature effects on the material scale depend on the materials used in the concrete mixture and the level of temperature regardless of the mechanical testing type. Most of the previous literature agrees that

concrete does not exhibit serious compressive strength reduction when exposed to temperatures up to 400 °C [10], while some works reported strength increase within this range of temperature [11]. However, effective chemical and physical changes occur after exposure to temperatures higher than this range [12, 13].

It is widely known that typical impact tests are costly ones and require great efforts and mostly large test specimens. Among these tests is the instrumented drop-weight impact test, which was utilized as a reliable testing method to evaluate the structural performance of reinforced concrete beams and slabs under falling impact loads. The ACI 544-2R [14] repeated impact test follows the same fundamental testing procedure of the instrumented drop-weight impact test. This test is conducted on small specimens and requires simple testing drop-weight manual procedure. This test does not require the installation of any kind of sensors and therefore does not require any data collecting systems. Hence, the ACI 544-2R repeated impact test can be considered as simple and easy method to perform repeated drop-weight impact loading. However, this test is not intended to be used as a quantitative tool to measure the impact strength of concrete due to the high variability of its results [15-17]. Instead, it is a qualitative test that evaluates the impact performance of fiber-reinforced mixtures and compare between the performances of different mixtures [14].

During the last few decades, fibrous concrete became a solution with a high strain energy capacity to resist the destructive action of impact loads. Different metallic and synthetic fibers were used to introduce new concrete mixtures with significant high impact energy resistance. Among these types are the high-performance and ultrahigh-performance concrete, preplaced aggregate fiber-reinforced concrete, self-healing concrete and engineered cementitious composites (ECC). The ACI 544-2R test was used by many researchers during the last 20 years to evaluate the effect of steel fibers [18-23], polypropylene fibers (PP) [24-26] and other synthetic fibers [27, 28] on the impact performance of concrete. Other works used this test to evaluate the impact response of high performance concrete [29], rubberized concrete [30, 31], preplaced aggregate concrete [32-36], and ECC [27, 28, 37]. However, a very few research works tried to investigate the thermal-repeated impact performance of fibrous concrete after exposure to elevated temperature [38-42].

The above reviewed literature reveals that the 400 °C temperature can be considered as a threshold beyond which the heating becomes significantly effective on concrete behavior. As ECC is one of the modern construction material types that possess distinguishable energy absorption capacity, an experimental program was directed in this study to investigate the effect of exposure to 500 °C on the repeated impact performance of ECC incorporating PP fibers. To better understand the post-heating impact response of ECC, similar specimens were made of normal strength conventional concrete for comparison purposes, heated to the same level of temperature and tested under the same conditions.

2. THE ACI 544-2R REPEATED IMPACT TEST

The repeated impact test is a simple procedure recommended by ACI 544-2R [14] following the classical drop-weight test. The testing procedure is very simple and does not need using load, displacement and vibration sensors or any other sophisticated measurement data loggers, while the used specimens are small and easy to produce, which make it a low-cost alternative to study the impact performance of concrete. The test is simply composed of a free drop-weight system that releases a weight of 4.54 kg from a vertical distance of 457 mm on a steel ball that tops a shallow concrete cylinder, which has a diameter of approximately 150 mm and a depth of approximately 64 mm. The specimen should be held using a special frame with four lateral supporting lugs fixed on a stiff baseplate as shown in Figure 1. Before testing, small elastomer pieces should be inserted between the concrete specimen and the holding steel lugs to prevent the specimen rebound after impacting. The test is initiated by freely dropping the weight on the steel ball that transfers the impact load to the specimen. The impact is repeated several times until the appearance of the first surface crack. At this stage, the testing is paused and the elastomers are removed after recording the number of impact blows as the cracking impact number (N1). Then after, the test is resumed until the fracture of the specimen so that at least three of the four steel lugs are touched by the concrete specimen. The number of impact blows at this stage is recorded as the failure impact number (N2), which declares the end of the test. The ACI 544-2R suggested using a manual frame, where the weight is lifted by hand. In this study, the electrical automatic testing machine shown in Figure 2 was used considering all the specifications and recommendations of the ACI 544-2R repeated impact test.

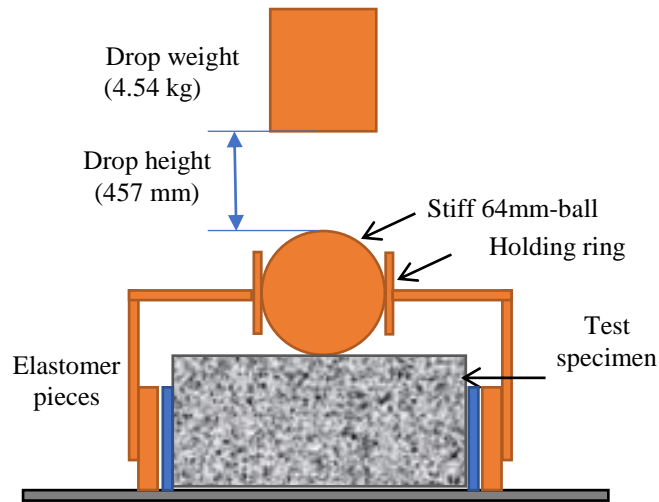


Figure 1 Mechanics of the ACI 544-2R repeated drop-weight impact test



Figure 2 The automatic drop-weight testing machine

3. MIXTURES, MATERIALS AND TESTING PROGRAM

Basically, the current work incorporates the preparing and casting of two different concrete types, which are the normal concrete (NC) and the engineered cementitious composite (ECC). The details of both mixtures are shown in Table 1. Both mixtures were designed to achieve an equivalent 28-day design compressive strength of approximately 40 to 45 MPa, while the constituents of both mixtures are different. However, one type of cement was used for both mixtures, which was an ordinary Portland cement type 42.5R with a specific gravity of 3.15 and a specific surface area of 368 m²/kg. The chemical composition of the cement is described in Table 2. For the NC mixture, natural sand with a fineness modulus of 2.46 and crushed gravel with a maximum size aggregate of 12.5 mm were used as fine and coarse aggregates, respectively.

ECC mixtures usually include no fine and coarse aggregates as in traditional concrete; instead, fine graded silica sand is usually used as the only mixture filler. In this study, silica sand with minimum/maximum grain size of 80/250 μm and a bulk density of 1500 kg/m^3 was used. In addition to cement, the binder of the ECC mixture included a significant quantity of fly ash as it is clear in Table 1. The fly ash specific gravity was 2.2, while its fineness as a percentage retained in the 45 μm sieve was 29%. The chemical composition of the used fly ash is detailed in Table 2. The adopted ECC mixture is the well-known M45 [43, 44] mixture that is reinforced with PVA fibers. However, due to the high cost of this type of fiber, low-cost PP fiber was used instead. The fibers were provided with 12 mm length and 32 μm diameter, while the density, tensile strength and elastic modulus of the fibers were 910 kg/m^3 , 400 MPa and 4 GPa, respectively. The used fiber volumetric content was 2%, which means that the used fiber weight in the mixture was 18.2 kg/m^3 . Due to the use of fibers and the high cement and fly ash content, Sika ® ViscoCrete 5930-L superplasticizer was used in only the ECC mixture with a dosage of 4.9 kg/m^3 .

From each mixture, 12 shallow cylinders with 150 mm diameter and 64 mm depth were cast to perform the repeated impact test, while 6 cubes and 6 beams were cast to perform the compressive strength and flexural strength tests, respectively. The cubes were 100×100×100 mm and the beams were 100×100×400 mm. Figure 3 shows a group of cast specimens. Six shallow cylinders, 3 cubes and 3 beams were used to perform the tests of the unheated specimens, while similar numbers of specimens were heated to 500 °C and tested after being cooled. The furnace shown in Figure 4a was used to heat the specimens to 500 °C at an approximately fixed heating rate of 4 °C/min [37-39]. A steel cage was used to protect the furnace walls from the possible thermal explosive failure of specimens as shown in Figure 4b. The specimens were then kept at this temperature for 60 minutes to assure a thermal saturation state [37-39], then the door of the furnace was opened and the hot specimens were left to slowly cool at the laboratory environment until the next day.

Table 1 Mixtures details

Mixture	NC	ECC
Cement (kg/m^3)	410	570
Fly ash (kg/m^3)	-	684
Natural sand (kg/m^3)	787	-
Crushed gravel (kg/m^3)	848	-
Silica Sand (kg/m^3)	-	455
PP Fiber (kg/m^3)	-	18.2
Tap Water (kg/m^3)	215	330

Table 2 Chemical composition of cement and fly ash

Oxide (%)	Cement	Fly ash
SiO ₂	20.08	56.0
Fe ₂ O ₃	3.6	24.81
Al ₂ O ₃	4.62	5.3
CaO	61.61	4.8
MgO	2.12	1.48
SO ₃	2.71	0.36



Figure 3 Cast specimens; beams, shallow cylinders and cubes



Figure 4 The used electrical furnace

4. RESULTS AND DISCUSSION

4.1 Compressive Strength

The compressive strength behavior after exposure to elevated temperatures has been a point of disagreement between interested researchers during the few past decades. However, there is a wide agreement that the behavior is highly controlled by the mixture constituents, type of aggregate and heating procedure. In this study, the residual strength heating scenario was adopted. Figure 5 shows the effect of hearing to 500 °C on the compressive strength of normal strength conventional concrete and ECC. It is obvious in the figure that before exposure to temperature, the compressive strength of NC specimens was 43.2 MPa, while that of ECC was 57.5 MPa. After exposure to 500 °C, the compressive strength of NC retained 77.6% of the original strength recording 33.5 MPa, while the residual compressive strength of ECC was 34.3 MPa, which is approximately equal to that of NC. However, comparing to the ECC unheated strength, the residual strength retained a lower percentage compared to NC, which is 59.7%. Thus, ECC compressive strength deteriorated at a faster rate compared to NC when exposed to 500 °C.

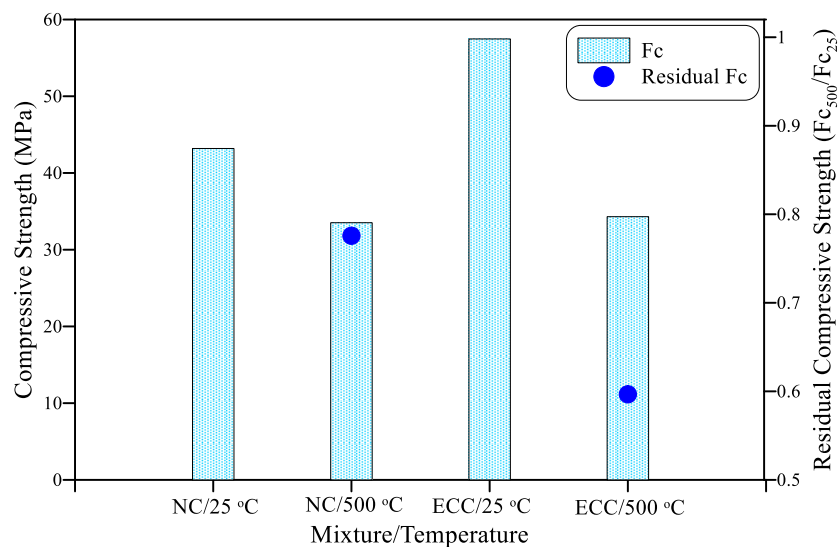


Figure 5 Residual compressive strength of NC and ECC specimens

The higher siliceous aggregate concrete in NC mixture is most probably the cause of the better thermal behavior of this mixture, which led to lower deterioration compared to ECC. On the other hand, ECC includes distinguishably higher content of cementitious materials, which imposes more internal thermal cracks and hence

quicker strength deterioration. A previous study on ECC [38] reported a similar trend of high compressive strength reduction after exposure to temperatures higher than 400 °C, which was attributed to the dense microstructure of ECC due to the high volume of fine materials and the absence of fine and coarse aggregates. It was reported that heating to temperatures higher than 400 °C increases the pore size several times due to the deterioration of the microstructure, which is the cause of the high strength reduction [45, 46]. On the other hand, other previous studies [13, 47] showed that conventional normal strength concrete with siliceous aggregate retained higher than 70% when exposed to temperatures around 500 °C. It should also be mentioned that the Eurocode EN1992-1-2: 2004 [48] specified a 60% residual strength for normal strength siliceous aggregate concrete, which is also in alignment with strength reductions reported by other previous studies [2, 49].

4.2 Flexural Strength

In literature [10, 50, 51], it was reported that the flexural strength generally exhibits higher percentages of strength reduction compared to compressive strength when exposed to elevated temperatures. A similar trend of results was also recorded in this study, where the reductions in both concrete types after exposure to 500 °C were higher than the corresponding reductions in compressive strength. Before heating, the flexural strength of ECC was distinguishably higher than that of NC, where the flexural strength records were 3.7 and 6.9 MPa for NC and ECC, respectively. The better performance of ECC in flexure is attributed to the higher plastic strain absorptivity of ECC due to the fine dense microstructure and the presence of PP fibers. Where fibers play the main role in crack bridging that leads to a more ductile multi-cracking performance, which in turn alters the failure and increases the flexural capacity [52, 53]. As shown in Figure 6, NC retained 1.6 MPa, while ECC retained 3.0 MPa after exposure to 500 °C. This means that the residual flexural strength of both NC and ECC was approximately 43% of their original unheated strengths. The melting and evaporation points of PP fibers are approximately 180 and 350 °C, respectively, which means that fibers already evaporated after exposure to 500 °C. When fibers evaporate they leave continuous voids in the microstructure, which weakens the material further. Therefore, ECC exhibited a high flexural strength reduction, while its original strength was significantly superior compared to NC. One of the main causes of the strength deterioration after exposure to high levels of temperatures exceeding 400 °C is the dehydration of cementitious hydrated products, which imposes extensive microstructural cracking and noticeably weakens the material [54, 55]. This chemical effect was another cause of the deterioration of the flexural strength of NC and ECC. Previous studies [56, 57] on ECC mixtures reinforced with PVA fibers reported similar trends of flexural strength reductions as those obtained in this study when the specimens were exposed to temperatures ranging from 400 to 600 °C.

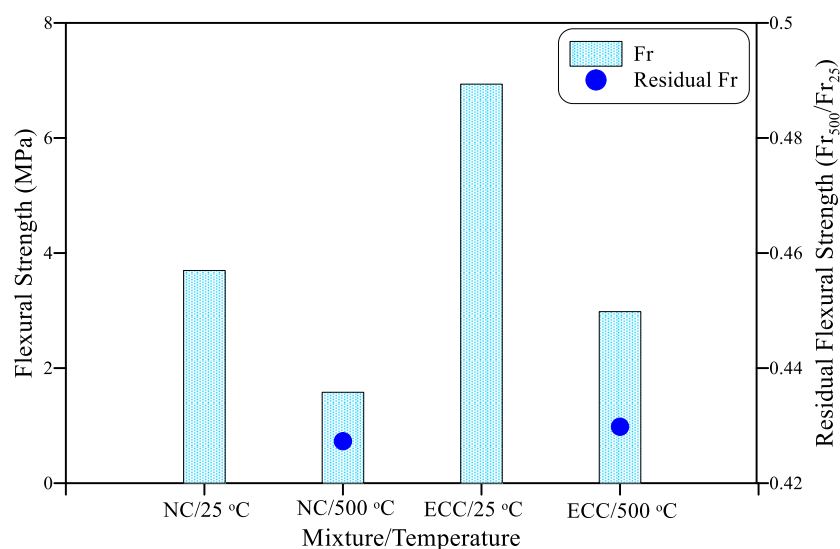


Figure 6 Residual flexural strength of NC and ECC specimens

4.3 Impact Strength

As preceded in section 2, the impact performance of the tested shallow cylindrical specimens is measured in terms of cracking impact number (N1) and failure impact number (N2). The N1 records of NC and ECC specimens are depicted in Figure 7, while Figure 8 shows the N2 records of both mixtures at normal and high temperatures. Figure 7 shows that N1 records of NC mixture was higher than that of ECC for the unheated specimens. For the specimens tested without heating, the recorded N1 values were 55 for the conventional concrete mixture and 43.3 for the ECC mixture. The higher cracking impact strength of NC can be attributed to the presence of the stiff coarse siliceous aggregate particles that can withstand higher impact loads than the soft cement paste. On the other hand, ECC microstructure is composed of dense and fine high-cementitious content material. The retained N1 of NC after exposure to 500 °C was much lower than that of ECC, where N1 of NC was 2.2, while that of ECC was 10.3 blows. This means that the residual cracking impact strength after exposure to 500 °C was approximately 4% for NC and 24% for ECC as shown in Figure 7. This can attributed to the same reason, where the presence of aggregate in NC leads to more severe differential thermal movements due to the different thermal expansions of the aggregate particles and cement paste [58-60], which leads to a further strength deterioration added to the chemically induced effects of C-S-H dehydration [61, 62].

The fiber was not effective in ECC during the precracking stage, which resulted in low N1 records. This is because the function of fibers was not effectively initiated yet before cracking. However, after the cracks spread in the microstructure due to the increase of impact forces owing to the increase of the number of impact blows, fibers become highly functional to bridge these cracks by connecting the two sides of the crack and withstanding the tensile stresses imposed from impact loading [63]. Therefore, the recorded failure impact number of ECC increased dramatically compared to that of NC. As shown in Figure 8, the N2 record of NC was only 57.2 blows, while that of ECC was 259.3 blows before heating. However, the effect of fibers in crack bridging and increasing the impact resistance was vanished after exposure to 500 °C due to the evaporation of fibers. Therefore, the percentage residual N2 of both NC and ECC mixture were approximately equal, which were 5.2 and 4.5%, respectively.

The available literature on repeated impact of different concrete types after exposure to high temperature agrees with the finding of this study. In general, two major findings can be summarized. The first is that the impact strength deteriorates at a higher rate compared to compressive strength when exposed to high temperatures, which was also distinguished by previous studies [39, 40, 42]. This behavior was attributed to the hysterical tensile stress waves due to the repeated drop-weight impacts compared to the steady compression stresses under compression loads [41]. The second finding is that synthetic fibers like PP are effective before heating in enhancing the impact resistance, while after exposure to temperatures higher than their melting point, this effect is reversed and becomes an additional cause of deterioration, where fiber evaporation leaves behind a brittle porous media [37, 38].

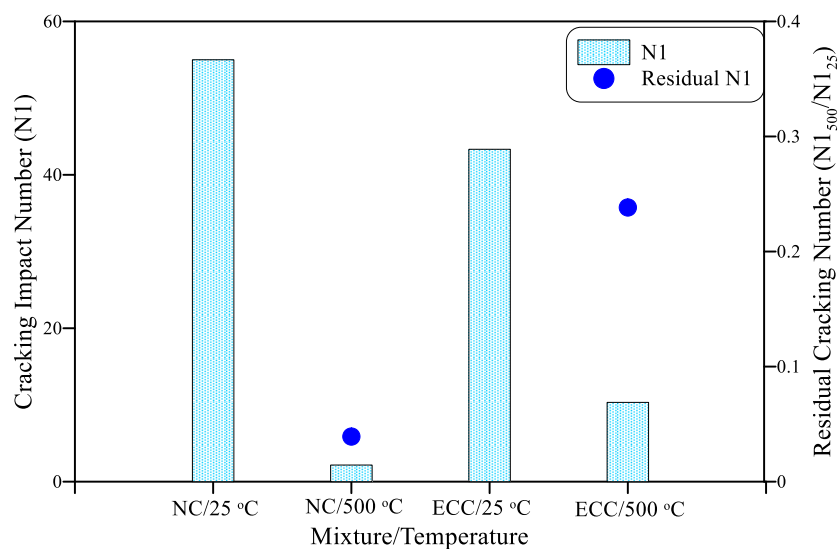


Figure 7 Residual cracking impact numbers of NC and ECC specimens

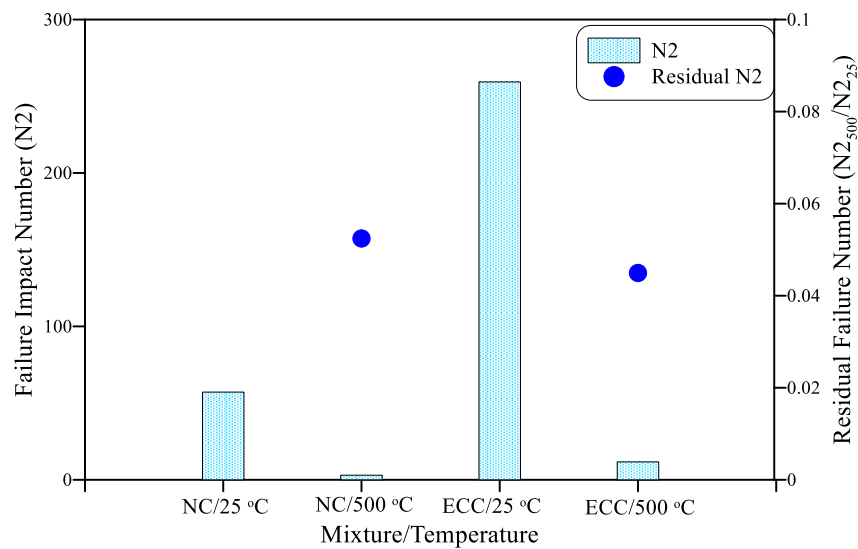


Figure 8 Residual failure impact numbers of NC and ECC specimens

4.4 Impact Ductility

The effect of fibers is also verified using the impact ductility index, which measures the ductility of the specimen based on the recorded cracking and failure impact numbers. The impact ductility index (ID) is simply the ratio of N2 to N1 ($N2/N1$), which is derived from the flexural ductility index, where the ultimate displacement is divided by the yield displacement to show the amount of plastic energy absorbed by the material. The impact ductility index was used by recent studies [64, 65] to highlight the ability of fibers to improve the ductility of concrete under impact loads. Figure 9 shows the recorded ID for NC and ECC specimens before and after exposure to 500 °C.

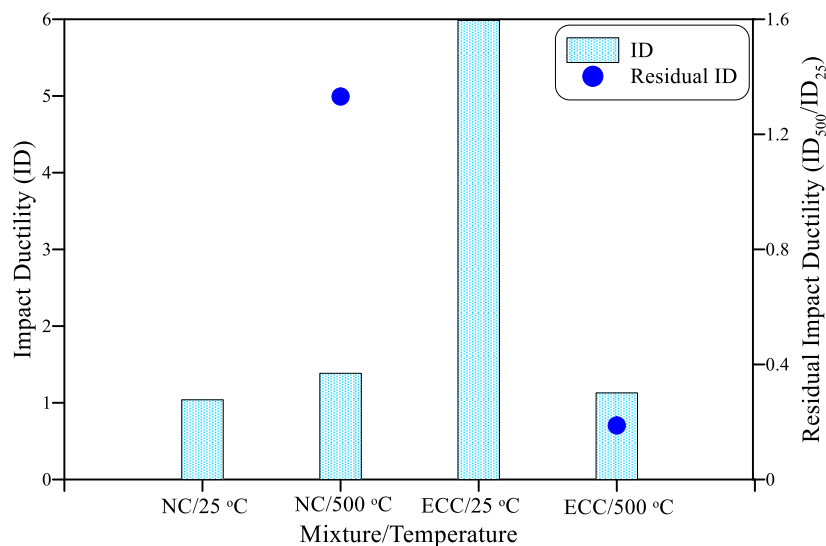


Figure 9 Residual impact ductility of NC and ECC specimens

It is clearly shown in the figure that for the reference unheated specimens, ID for NC was only 1.04, which reflects an approximately ideal brittle behavior, where the specimens failed due to only 2 more impact blows after cracking reflecting a sudden brittle failure. Oppositely, the ductility index ID of ECC was much higher than that of NC, which was 5.98. Thus, it is approximately 6 times that of NC. This number reflects a very ductile behavior where 216 additional impact blows were required to fail the ECC specimens after being cracked. The superior ductility of ECC is attributed to its high strain absorptivity capacity, which arises from its fine dense microstructure with high cementitious materials content and the presence of 2.0% of synthetic fibers. Such a material can behave a distinguishable multi-cracking during the plastic phase after the first surface crack becomes visible. However, after exposure to 500 °C, the microstructure was significantly weakened and the fibers were

evaporated as discussed earlier, which eliminated the strength points of ECC that led to its high ductility. Therefore, as shown in Figure 9, both NC and ECC exhibited brittle failures with low ID records after exposure to 500 °C.

5. CONCLUSIONS

- 1- The ECC specimens retained lower percentage residual compressive strength compared to NC, where the residual compressive strengths of NC and ECC after exposure to 500 °C were approximately 78 and 60%, respectively. The presence of large amount of siliceous aggregate in NC increases its resistivity to thermal degradation, while the high amount of soft cementitious paste and the evaporation of PP fibers increased the pore size in ECC and led to higher deterioration rate.
- 2- Due to the fine microstructure of ECC and the incorporation of PP fibers, its unheated flexural strength was approximately 1.9 times that of NC. However, both ECC and NC exhibited high flexural strength reductions after exposure to 500 °C, where the residual flexural strengths of both mixtures were approximately 43% of their original unheated strengths.
- 3- Before heating, the presence of tough siliceous aggregate particles enabled NC specimens to record higher cracking impact strength than ECC, while ECC exhibited much lower percentage deterioration after exposure to 500 °C.
- 4- Owing to its microstructure and the bridging activity of PP fibers, ECC retained superior failure impact resistance compared to NC, where the NC specimens failed after only 2 additional impact blows after cracking, while more than 200 impact blows were required to fail the cracked ECC specimens. The failure impact numbers of NC and ECC were approximately 57 and 259 blows, respectively. Therefore, ECC exhibited a significantly ductile behavior compared to the brittle failure of NC. The impact ductility index of ECC was approximately 6 times that of NC.
- 5- After heating to 500 °C, the failure impact strengths of both NC and ECC deteriorated at a fast rate losing approximately 95% of their unheated failure impact strengths. The harsh degradation of ECC is attributed to the weakened microstructure due to the thermo-chemical changes of hydrated products and the evaporation of PP fibers that resulted in a more porous structure.

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