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Does Metakaoline Replacement Adversely Affect the Cyclic Behavior of Non-Strengthened and Strengthened RC Beams: An Experimental Investigation

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Abstract: The need to reduce carbon emissions has recently become prevalent in light of concerns related to climate change. Since the cement industry causes approximately 8% of global CO_2 emissions, it might be an urgent necessity to include cement replacement materials within the concrete industry. An important question arises about if such replacement negatively affects the cyclic or seismic behavior of reinforced concrete (RC) elements. This research presents an experimental investigation of the effect of using different percentages of metakaolin replacement on the monotonic and cyclic behavior of RC beams. The investigated parameters include the flexural strength, ductility and energy dissipation capacity of the tested beams. The current paper also aims to study the effect of using the CFRP-strengthening technique with 15% metakaolin replacement on the behavior of RC beams under the same loading protocols. The experimental results reveal that metakaolin can be used as a partial substitute for cement up to 20% without negative effect on the concrete behavior under both loading protocols. For cyclic loading, the percentage of replacement did not negatively affect the ductility; rather, it provided some improvement.

Keywords: environmentally friendly concrete; partial replacement of cement; metakaolin; RC beams; cyclic loading; monotonic loading; CFRP stripping; strengthened beams

Citation: Elwardany, H.; Moubarak, A.M.R.; Abu el-hassan, K.; Seleemah, A. Does Metakaoline Replacement Adversely Affect the Cyclic Behavior of Non-Strengthened and Strengthened RC Beams: An Experimental Investigation. *Buildings* **2022**, *12*, 719. https://doi.org/10.3390/buildings12060719

Academic Editors: Shazim Memon, Arsalan Khushnood, Asad Hanif, Luciana Restuccia, Marco Di Ludovico and Antonio Caggiano

Received: 5 April 2022
Accepted: 23 May 2022
Published: 26 May 2022

1. Introduction

The cement production industry contributes significantly to the problem of climate change. More than four billion tons of cement produced annually is responsible for about 8% of global CO_2 emissions [1]. Moreover, annual cement production is expected to increase up to 5 billion tons over the next 30 years. Consequently, there has arisen an urgent necessity to include cement replacement materials within the concrete industry. Several materials such as metakaolin, silica fume, fly ash and rice husk ash have been studied as substitutes for a portion of cement [2,3]. An improvement in the porosity, concrete strength and workability of the concrete mixture were observed by using these materials. Moreover, they resulted in a reduction in the calcium hydroxide concentration during pozzolanic reactions [4–6].

Metakaolin is basically refined kaolin clay that is fired under carefully controlled conditions to create an amorphous aluminosilicate that is reactive in concrete. The particle size of metakaolin is generally smaller than cement particles. As a pozzolanic material, it consists of highly efficient pozzolana and reacts rapidly with the excess calcium hydroxide resulting from cement hydration to produce calcium silicate hydrates (CSH) and calcium aluminosilicate hydrates [7–9]. Among its benefits are its low cost and the fact that it saves energy and reduces the emission of carbon dioxide into the atmosphere.

The effect of using metakaolin (MK) as a cement replacement with different percentages (10 and 15%) was studied by Muralinathan et al. [10]. The results show an improvement in the strength of concrete with 10% metakaolin compared to 15% as well as conventional concrete. It is also observed that the addition of metakaolin led to the acceleration of the hydration process and the formation of C-S-H gel which led to an increase in concrete strength. Saboo et al. [11] studied the effect of using both fly ash and metakaolin as partial replacements of cement. Different concrete properties such as porosity, permeability, density and compressive strength were tested. A significant increase in the density and decrease in porosity was observed when adding 2% of metakaolin.

The addition of 10% of metakaolin improved the 7-day compressive strength 4 times higher than the conventional concrete [12]. Moreover, the micro-filler effect as well as the additional C-S-H gel formation enhanced the binders' interfacial bond. Using both alkali-resistant glass fibers and 10% metakaolin increased the concrete flexural strength up to 19% [13]. Increasing the percentage of metakaolin up to 15% increased both the compressive and flexural strength of concrete, whereas it reduced the concrete workability where the slump values decreased from 63 mm for 0% metakaolin to 40 mm for 25% of metakaolin as cement replacement [14]. Much research has been conducted to determine the optimal percentage of metakaolin as a partial cement replacement; some have recommended 15% [15], while others have found that 10% is the optimal ratio [16–18].

The effect of metakaolin on different concrete properties was studied [19]. An improvement in the compressive strength when using (5, 10, 15 and 20%) of metakaolin was observed as it was (10.0, 21.0, 28.3 and 25.2%) at an age of 28 days, respectively, for 350 Kg/m^3 cementitious content, whereas the improvement was (11.7, 23.1, 30.7 and 27.1%) when using (5, 10, 15 and 20%) of metakaolin, respectively, at 450 Kg/m^3 cementitious content. The effect of different percentage of metakaolin (5, 10 and 15%) on various properties of concrete was also studied [20]. The results revealed that an enhancement in the strength of concrete at all ages was observed when increasing the replacement level. An experimental investigation [21] studied the effect of metakaolin as a partial cement replacement on the behavior of a concrete pier. The results show that the maximum concrete strength was obtained with 10% metakaolin after both 7 and 28 days.

Several studies experimentally investigated the effect of the cyclic loading on the response of beams. For example, Chalioris et al. [22] studied the effect of using different volumetric volume of steel fibers (1% and 3%) on the cyclic response of RC beams. Three beams of 200 × 200 × 2500 mm were experimentally tested under four-point bending load. The results show an improvement in the overall hysteretic response. The flexural behavior of high-strength concrete beams reinforced with basalt fiber-reinforced polymer (BFRP) was investigated by [23]. A total of five concrete beams of 150 × 300 × 2100 mm were tested under the effect of four-point bending cyclic loading. Different reinforcement ratios (ρ_f) of BFRP were used and one conventional beam was the control beam (S77). The results show that in beams with larger BFRP ratios, residual stiffnesses were higher. More studies considering the effect of cyclic loading on the response of different concrete types and members were conducted by [24,25].

The effect of loading rate on the cyclic behavior of reinforced concrete beams was studied by Xio et al. [26]. Displacement control loading with different loading rate from 0.1 to 10 mm/s was applied to the tested beams. The results revealed that the same failure mode was observed for the tested beams and more uniform distribution of the crack was observed with increasing loading rate. Furthermore, increasing the loading rate increased the strength, displacement and energy dissipation. On the contrary, a reduction in the ductility was observed with increasing loading rate.

According to the authors' knowledge, the experimental studies on both strengthened and non-strengthened beams with different percentage of metakaolin as a cement replacement under cyclic loading are very limited. For example, Shankar and Suji [27] investigated the flexural behavior of high-performance concrete beams under static cyclic loading. A total of eight reinforced concrete beams were tested; four of them were conventional concrete and the others were replaced by 10% metakaolin as a cement replacement and 30% of quarry dust as a sand replacement. The results indicated that the capacity of the load is increased by 8.33% to 26.67% after 28 and 56 days as compared to concrete beams without replacements. Moreover, it slowed down the first crack formation and a smaller deflection was observed. The results also showed an increase in both the compressive strength as well as the tensile strength with the increase in concrete age.

Different strengthening techniques for RC beams, such as jacketing, FRP stripping, textile-reinforced matrix (TRM) shells, woven fiber bonding, externally bonded steel plates (EBSP) and near-surface mounted (NSM) steel rebar are used and some of them were presented in different research [28–34]. Moubarak et al. [31] experimentally studied the effect of using metakaolin and silica fume as cement replacement materials on the behavior of RC beams. Different percentages of both materials ranging from 8 to 20% were used. Moreover, the test was performed under the effect of two equal monotonic loads. The results revealed that the optimum cement replacement ratio was about 8–12% for the relatively large-scale beams. While this research focused on the monotonic behavior of beams constructed via metakaolin replacement, it raised the need for the current study where the cyclic behavior of such beams is investigated. Tarigan et al. [32] experimentally compared the effect of using steel plates, CFRP and GFRP on the flexural strength of RC beams. The conclusion was that CFRP as an external reinforcement was a better choice than the others. Nine FRP-strengthened beams as well as three non-strengthened RC beams under cyclic loading were tested by Shrivastava R. et al. [35] to determine the stability point. Different configurations of tension face externally bonded FRP were used. The results show that FRP increased the flexural strength of beams and reduced the ductility as it showed catastrophic brittle failure.

2. Research Significance

As previously shown in the literature review, almost all the conducted studies focused on the response of beams with metakaolin as cement replacement under the effect of monotonic load. To the authors' knowledge, the experimental studies on both strengthened and non-strengthened beams with different percentage of metakaolin as a cement replacement under cyclic loading have not been conducted so far. This study is mainly concerned with reducing carbon dioxide "CO_2" emissions by using metakaolin as a cement substitute without affecting the concrete strength. Moreover, the study covers the lack of knowledge regarding the effect of downward cyclic loads on RC beams that contain different percentages of metakaolin as a cement replacement. These beams represent actual cases of simply supported beams in bridges or factories where the load is always acting downwards (vehicle loads in bridges and Clark loads in multistory factories where the loads can be represented by cyclic loading); see Ref. [36]. To accomplish this, static (monotonic) loading was conducted first to obtain reference deformation as well as information about the load deflection curve especially in the post-elastic phase; refer to NEHRP [37]. Then, a displacement-controlled cyclic loading protocol was designed such that the loading will always act downwards taking into consideration the expected plastic deflection. Moreover, to obtain a preliminary insight about any future need to strengthen beams constructed via metakaolin replacement and whether the existence of metakaolin will cause an adverse effect, a beam containing metakaolin was strengthened using external CFRP and tested under the effect of cyclic loading.

The current investigation aims to:

1. Assess the most environmentally friendly concrete mix through the optimum cement replacement by metakaolin.
2. Study the effect of metakaolin as a partial substitute for cement on the cyclic performance of RC beams.
3. Explore the applicability of strengthening beams constructed using metakaolin replacement and figure out whether the existence of metakaolin will cause a negative effect on their cyclic performance.

4. To perform an experimental investigation utilizing relatively larger-scale specimens to capture closer behavior to real life applications.

3. Research Program

In the current research, ten simply supported concrete beams with a cross section of 120 × 200 mm and 2000 mm length were tested (see Figure 1). Two loading programs "Cyclic/monotonic" with four-point bending load were applied on eight non-strengthened "bare" beams as well as two CFRP-strengthened beams, as summarized in Table 1. The load was applied using a pinned-end hydraulic actuator for cyclic load and a loading jack for monotonic load connected to a load cell. The mid-span deflection of beams was measured by linear variable differential transformers (LVDTs) (see Figure 2). In the cyclic loading, a displacement-controlled protocol with loading frequency of 0.05 HZ was used according to the cycles shown in Figure 3. Three cycles of loading were applied at each displacement amplitude according to NEHRP recommendation [37]. Special care was taken to assure that the specimen was always loaded in compression only (i.e., loading is always downwards). In both monotonic and cyclic tests, loading continued until reaching a failure condition. Both loads and deflections were continuously recorded during the experiment up to failure using a computerized data acquisition system. Different metakaolin "MK" cement replacements ranging from 8% to 20% were tested. Two beams were casted for each percent of "MK" cement replacement: one for the monotonic loading test and the other for the cyclic loading test. The casted mixes for one cubic meter of concrete and the corresponding characteristic strengths are shown in Table 2. Both physical and chemical properties of the used ordinary Portland cement (CEM-I 42.5) as well as the used aggregates and the properties of the local metakaolin "MK" are shown in Table 3. The used sand "fine aggregate" and the 5–12 mm well-graded dolomite "coarse aggregate" were chosen according to ASTM C33 [38]. In order to enhance the workability of the low water content admixture, Sikament 163 M (ASTM C-494 Type F) was used as a superplasticizer [39].

Table 1. Description of tested specimens.

Cement Replacement %	Specimens	Loading Criteria
0	RC	Monotonic
8	MK8	
15	MK15	
20	MK20	
15	MK15-CFRP *	
0	RC	Cyclic
8	MK8	
15	MK15	
20	MK20	
15	MK15-CFRP *	

* CFRP strips with end U-shaped wrapping.

Table 2. Concrete mixes' proportioning and strength parameters.

Slump (cm)	E_C (GPa)	f_{ct} +++ (MPa)	f_{cu} ++ (MPa)	Super Plast. (Lit.)	Water (kg)	w/c (%)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Metakaolin Replacement		Cement (kg)	Cement Replacement %	Mix
									%Volume +	Weight (kg)			
10.50	26.60	2.70	36	-	168	0.42	630	1145	0	0	400	0	RC
11	26.10	2.80	35	3.2	168	0.42	630	1145	10.24	32	368	8	MK8

Table 2. *Cont.*

Slump (cm)	E_C (GPa)	f_{ct} $^{+++}$ (MPa)	f_{cu} $^{++}$ (MPa)	Super Plast. (Lit.)	Water (kg)	w/c (%)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Metakaolin Replacement		Cement (kg)	Cement Replacement %	Mix
									%Volume $^{+}$	Weight (kg)			
10	27.50	2.90	37	6	168	0.42	630	1145	18.80	60	340	15	MK15
11	27.90	3.10	40	8	168	0.42	630	1145	24.70	80	320	20	MK20

$^{+}$ Percentage of volume of metakaolin/total volume of cement binder. $^{++}$ Compressive strength, $^{+++}$ Splitting tensile strength.

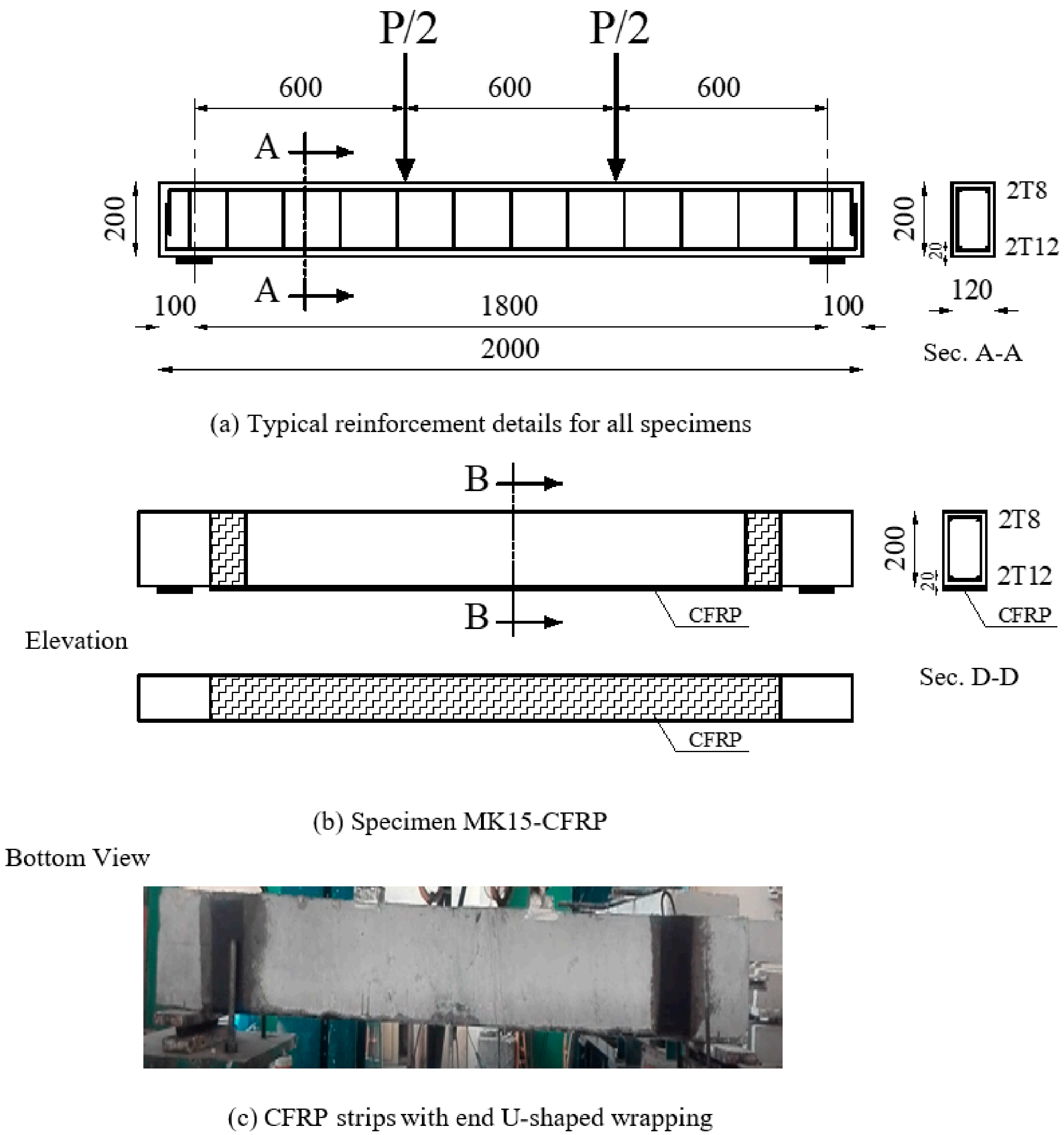


Figure 1. Specimen details.

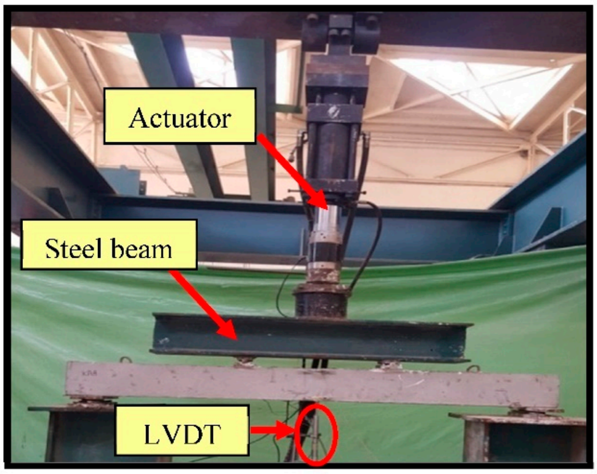


Figure 2. Experimental setup for cyclic testing.

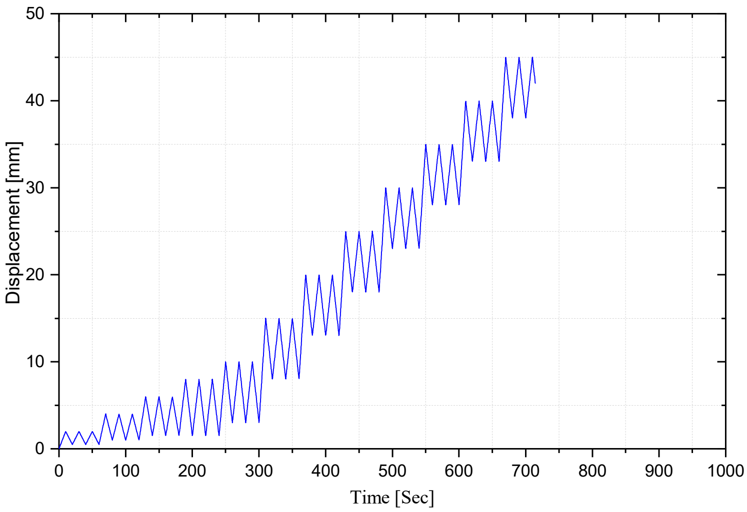


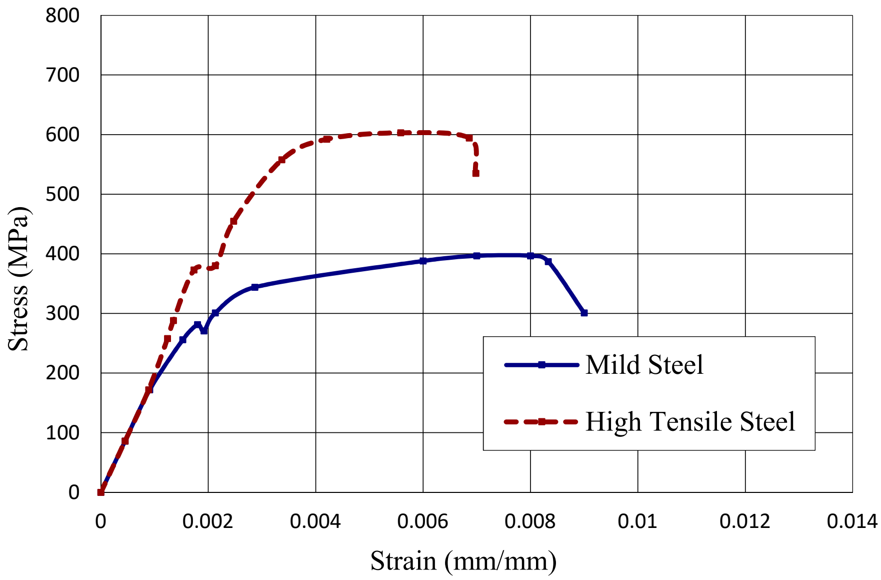
Figure 3. Displacement-controlled protocol.

Table 3. Properties of used cement, aggregate and MK.

Portland Cement (CEM I 42.5)		**Aggregate**			**MK**		
		Physical	**Coarse**	**Fine**			
Specific surface area (m^2/kg)	362	Specific weight	2.77	2.66	Specific gravity		2.40
Specific weight	3.15	Bulk density (t/m^3)	1.75	1.68	Color		Light pink
Soundness (mm)	1.0	Water absorption %	2.28	0.80	Chemical composition (%)	SiO_2	59.70
Initial setting time (min)	88	Crushing value %	21	—		Al_2O_3	30.90
						Fe_2O_3	2.60
Final setting time (min)	165	Coefficient of abrasion %	18.5	—		CaO	1.20
						MgO	0.15
Compressive strength of standard mortar after 28 days (MPa)	43.0	Fineness modulus	—	2.54		SO_3	0.03
						K_2O	0.60
						TiO_2	1.90
						Na_2O	0.50

Steel reinforcement with a 12 mm diameter and a nominal yield stress of 360 MPa was used as longitudinal bottom steel reinforcement. Moreover, 8 mm steel reinforcement with nominal yield stress of 240 MPa was used as longitudinal top steel reinforcement and stirrups. Figure 4 shows the test setup and the obtained stress–strain curve for both steel grades.

(**a**) Tension test setup



(**b**) Stress–strain curves of steel

Figure 4. The Mechanical Properties of the used steel "Experimentally obtained".

4. Observations on Non-Strengthened RC Beams

The observations of the experimental results for different cases of non-strengthened specimens listed in Table 1 are presented in this section. Discussions are made in terms of the results of cyclic loadings, as well as a comparison between the behaviors during cyclic versus monotonic loading.

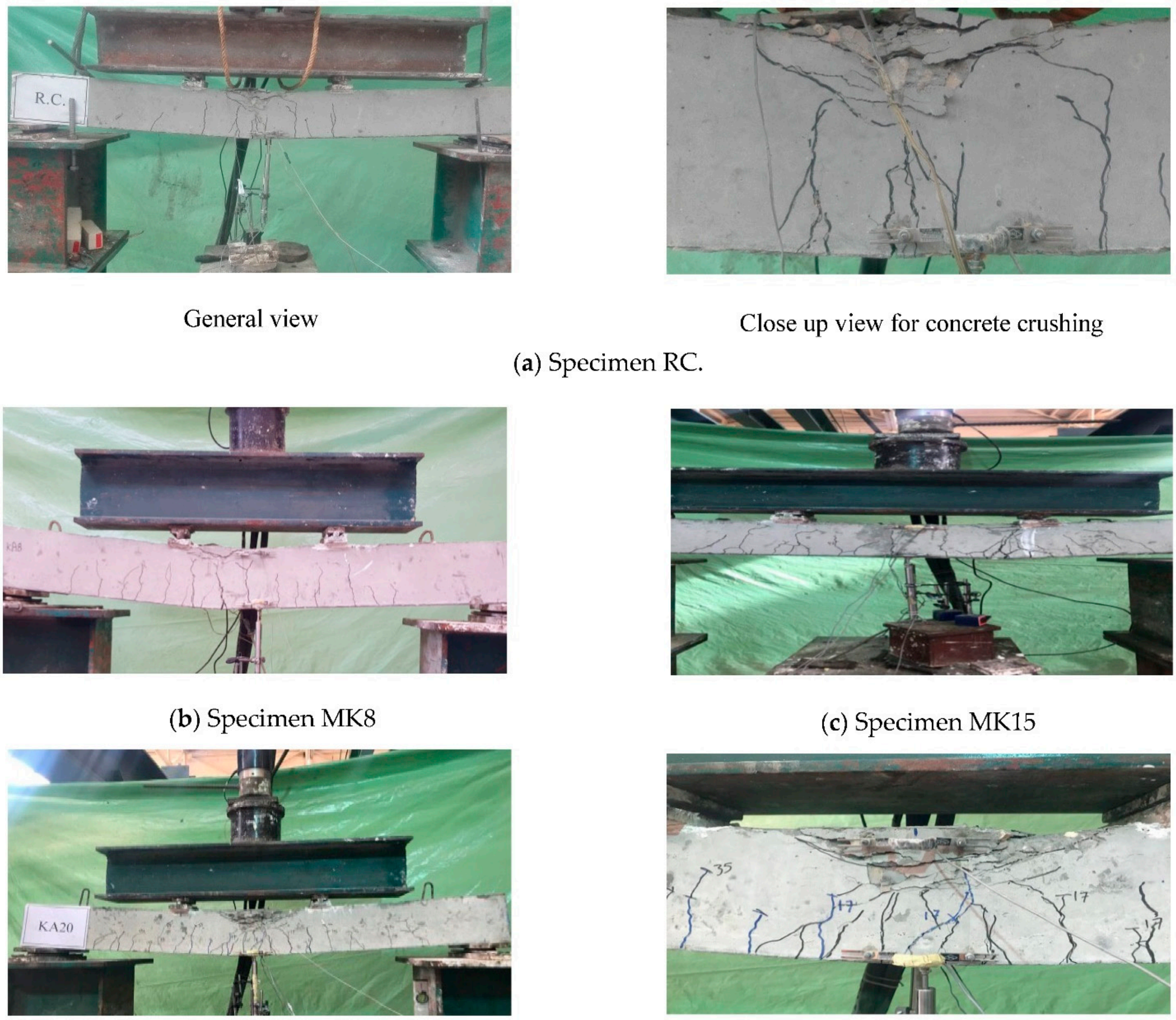
4.1. Shape of Failure and Crack Pattern

Regardless of the percentage of cement replacement, the failure mechanism and the crack pattern tend to be flexural failure, where the first vertical "flexural" crack appeared at the middle third of the beams due to tension at the bottom of the beam as a result of the pure bending. By increasing the load, cracks extended towards the top surface of the beam. Moreover, as a combination between the shear and bending moment, few diagonal hair cracks appeared closer to the supports (see Figure 5). At failure load, crushing of the concrete at the top of the middle of the beam was observed. It is worth noting that similar behavior was observed with the static loading cases (see Figure 6).

4.2. Load–Deflection Relationship

Figure 7 shows the load versus mid-span deflection for beams having different percentages of MK replacement. After the first cycle, the first crack occurred and a stiffness reduction was observed in all specimens. The yielding of the bottom "tension" reinforcement appeared after three cyclic loading groups for the RC, MK8 and MK15, whereas it appeared after four cyclic groups for MK20. Figure 8 illustrates the envelopes of the loading–displacement curves, where it clearly shows the behavior of each beam under the cyclic load. Generally, the initial stiffness was not significantly affected by the percentage of MK replacement as compared to the RC "control specimen". Furthermore, up to the yielding point, the observed stiffness of the cracked section was more or less the same for all specimens. The trend's multi-linear behavior is evident where, after the yielding point, the stiffness of all specimens degrades. The results indicated that stiffness of beams at the last cycle was significantly affected by the cement replacement where the percentage of the stiffness at the last cycle to the initial one, "%SL/SI", reached 45.50, 47.41 and 52.0 percent for 8, 15 and 20 percent MK replacement, respectively, as compared to 71% for the control beams "RC".

Despite the varied percentages of cement replacement, the maximum and ultimate loads were almost identical for almost all specimens (see Table 4). This is consistent with the results presented by Shankar and Suji [27] where a minor increase in the ultimate load capacity by only 8.33% after 28 days occurred with 10% metakaolin as a cement replacement.



General view

Close up view for concrete crushing

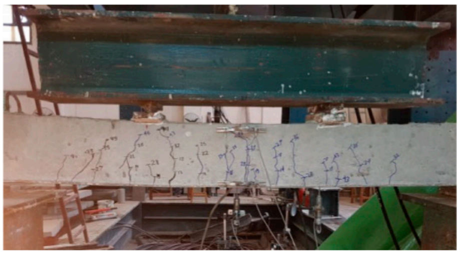
(**a**) Specimen RC.

(**b**) Specimen MK8

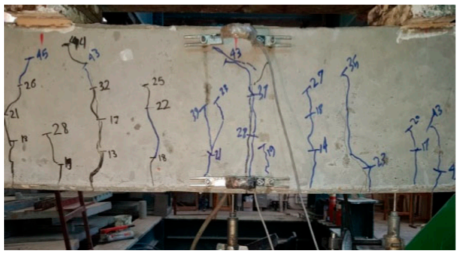
(**c**) Specimen MK15

(**d**) Specimen MK20

Figure 5. Crack pattern for bare beams "Cyclic loading".

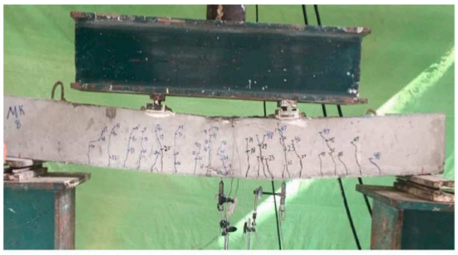


General view

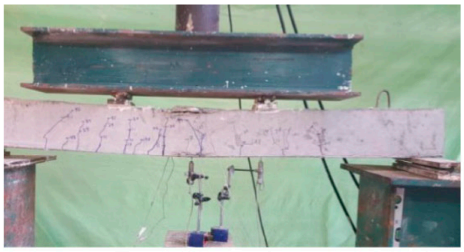


Close up view for concrete crushing

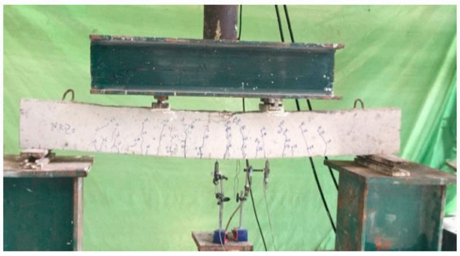
(**a**) Specimen RC.



(**b**) Specimen MK8



(**c**) Specimen MK15



(**d**) Specimen MK20

Figure 6. Crack pattern for bare beams "Monotonic loading".

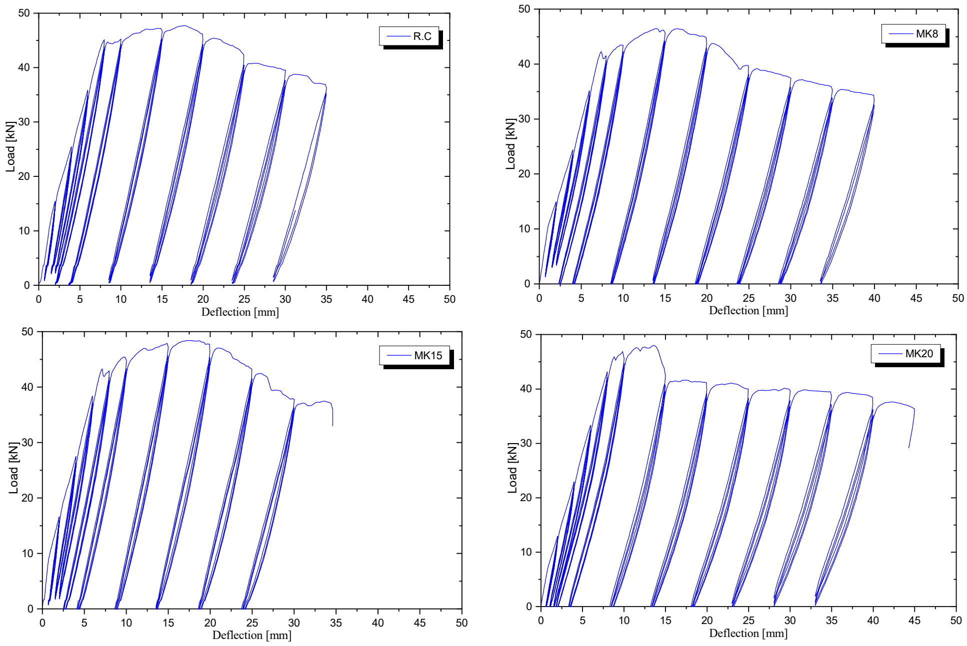


Figure 7. Load versus mid-span deflection for beams with MK replacement "Cyclic loading".

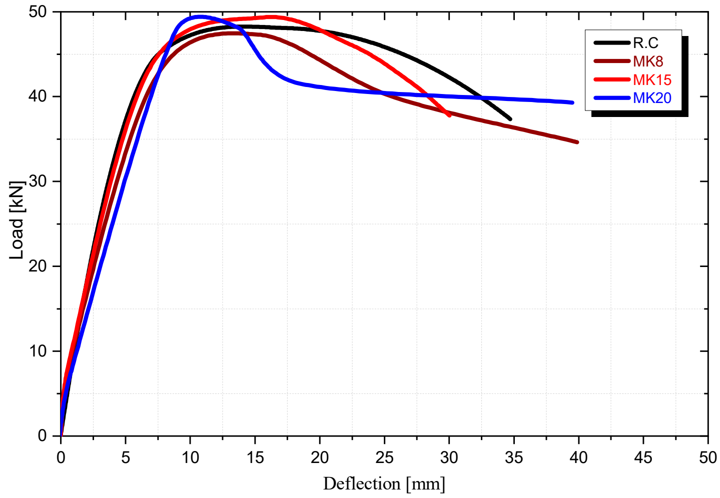


Figure 8. Envelope Curves for Load versus mid-span deflection, for beams with MK replacement "Cyclic loading".

Table 4. Load capacity and ductility of beams under cyclic loadings.

ID	Load at Yield, Py(kN)	Maximum Load, Pmax (kN)	Ultimate Load, Pu (kN)	Ductility (μ) +
RC	45.34	48.07	37.35	4.46
MK8	42.26	47.28	34.61	5.44
MK15	43.40	49.33	37.79	4.36
MK20	47.62	48.19	39.29	4.47

+ μ = maximum deflection/deflection at yield.

4.3. Effect of the Cement Replacement on Energy Dissipation Capacity

The ability of structural elements to dissipate energy while subjected to dynamic loads reflects the extent of that element's ability to withstand several cycles of reversed loading. Based on this importance, the effect of different percentage of cement substitutes on the total dissipated energy compared to the control sample "RC" was studied. The dissipated energy was calculated numerically by integrating the area under the load–deflection curve. Figure 9 shows that, at the initial stage "before yielding point", all specimens have more or less the same energy dissipation as the loading–unloading cycles almost coincide (see Figure 7), whereas after the yielding point and with the increase in deflection, the difference between the loading–unloading cycles was obviously clear; this reflects the degradation in the stiffness [23]. In MK8 and MK10, an increase in the total energy dissipation by about 10% as compared to the control RC beam was observed, while with 20% replacement, the deflection beyond the yielding point increased without significant degradation in the strength, where the enclosed area by the loading–unloading curve was almost similar at each displacement level. This allowed for more energy dissipation by about 31% as compared to the control RC beam; see Figure 7.

On the contrary to the previously shown behavior of the cyclic load, the monotonic results showed a decrease in the dissipated energy with increasing percentage of cement replacement by about 39% and 22% with MK15 and MK20, respectively, as compared to the RC beam, while a minor increase of about 10% was observed with MK8 (see Figure 10). This might be related to the ductility behavior, where for cyclic loading, the percentage of replacement did not negatively affect the ductility, while under the effect of monotonic loading, using more than 8% cement replacement reduced the ductility.

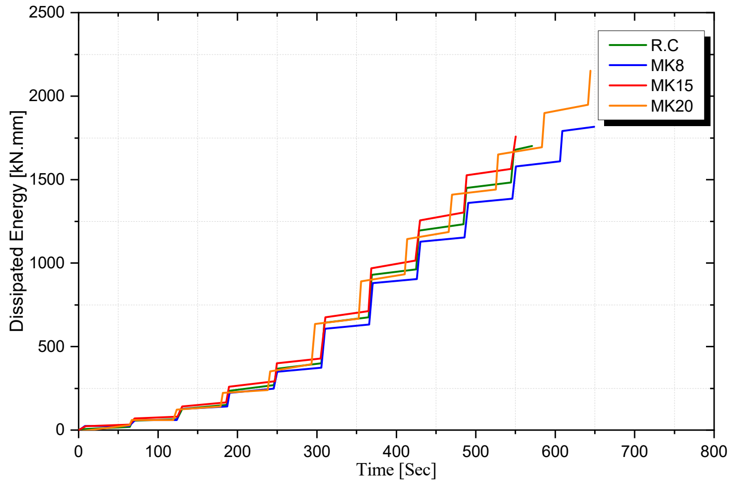


Figure 9. Envelope curves for the dissipated energy for beams with MK replacement "Cyclic loading".

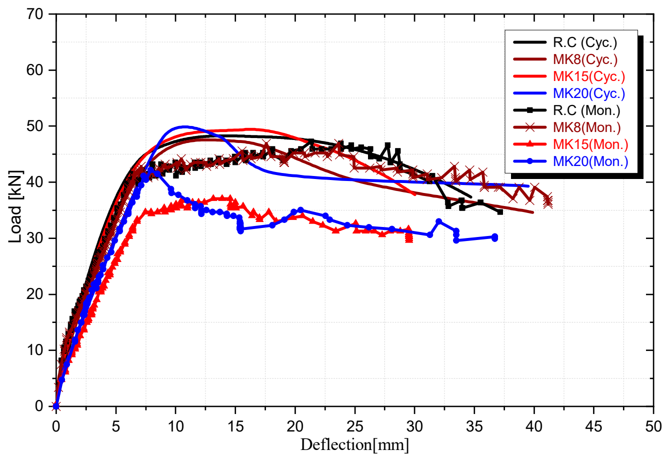


Figure 10. Comparison between load versus mid-span deflection for beams. Under "Monotonic (Mon.) and Cyclic (Cyc.) loading".

4.4. Comparison between Cyclic and Monotonic Loads for Non-Strengthened Beams

Only comparison between the monotonic and cyclic results will be performed here. For more discussion about the monotonic results, see [31]. Figure 10 clearly indicates that the initial stiffness before the first crack as well as the stiffness of the cracked section up to the yielding point was not significantly affected by the loading type, whereas a slight to moderate increase in both yielding and maximum loads for all beams under cyclic loading is observed, where the peak reached 31% and 33% with MK15, respectively, as compared to monotonic loading. The same behavior is observed with the ultimate load where it reached its maximum with MK20 with a 30% increase as compared to monotonic loading. Such behavior can be explained based on the difference in the steel behavior during the monotonic and the cyclic loading explained by Kaufmann et al. [40], where it was observed that the cyclic loading significantly increased the post-yielding stress as compared to the monotonic loading; see Figure 11. Moreover, it can also be related to the fact that loading type affects the modulus of elasticity of the concrete, where the ratio between the static modulus of elasticity (E_c) and the dynamic modulus (E_d) is always smaller than unity and ranges between 0.72 and 0.83 [41,42]. Furthermore, during the cyclic loading condition, the loading and unloading process gives the beams the chance to redistribute the applied loads and close the formed cracks during the unloading stage. These reasons integrate and cause an increase in both yielding and maximum loads under the cyclic loading as compared to the monotonic one.

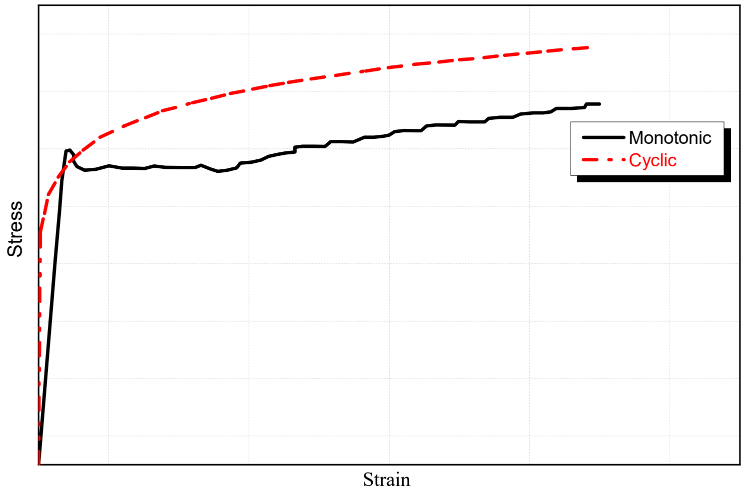


Figure 11. Comparison of Monotonic and Stabilized Cyclic Stress–Strain Behavior of Steel.

4.5. Ductility

Ductility can be described as a structure's ability to withstand inelastic deformations beyond its initial yield deformation while maintaining its load resistance [43]. The ductility index (DI) or factor (μ) has traditionally been used to assess the ductility. The ductility index (DI) or factor (μ) may be obtained using the following equation:

$$\mu = \frac{\Delta_{u}}{\Delta_{y}} \tag{1}$$

where (Δ_y, $\Delta_{u,}$) are the mid-span deflection of the beam at the yielding load and ultimate load, respectively.

Table 4 shows that the percentage of replacement did not negatively affect the ductility; rather, it provided some improvement, as in the case of MK8, where the ductility increased by 22% as compared to the RC specimen.

Figure 12 illustrates that a minor decrease in the ductility index "DI" for cyclic loading is observed as compared to the monotonic one. This can be attributed to the observation that the yielding displacements for both loads were close, but the displacement at failure under the monotonic loading was slightly larger. This might also be related to the higher dynamic modulus of elasticity "E_d" compared to the static one "E_s" [41,42].

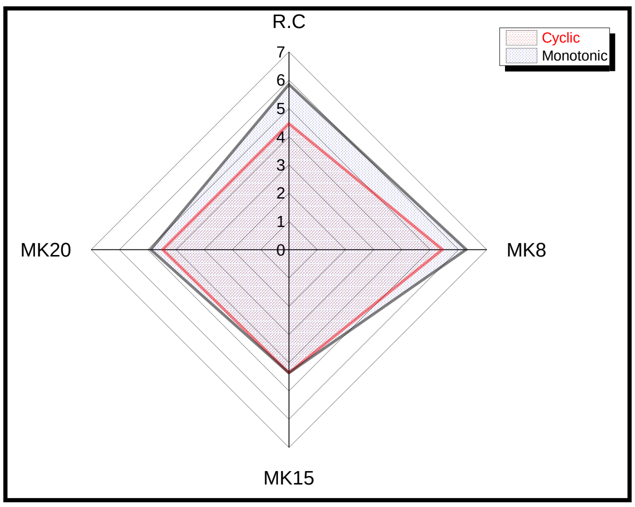


Figure 12. Comparison between "D.I" for monotonic and cyclic loading.

From the results of the current research, it may be concluded that metakaolin as cement replacement can be used up to 20% without a negative effect on the behavior of RC beams under cyclic or monotonic loading protocols, whereas previous studies [6,13,16,17,20,21] show that 10% was the optimum percent and others [14,19] noted that the optimum cement replacement was 15%. The difference in the optimum percentage might be related to the fact that the previous research was conducted using small-scale specimens under the effect of monotonic loading only.

5. Observation on Strengthened Beams

As a case study, two beams having MK replacement of 15% were strengthened by external unidirectional CFRP 120 mm-wide strips "SikaWrap"; see Table 1. As given in the manufacturer data sheet, the CFRP strips have a dry-fiber tensile strength = 4900 N/mm^2, modulus of elasticity in tension = 230,000 N/mm^2, and elongation at break = 1.7%. The fiber density is 1.80 g/cm^3 and the dry-fiber thickness is 0.129 mm. One beam was tested under cyclic loading while the other was tested under monotonic loading. Moreover, the fibers were wrapped at their ends with U-shaped cross fibers (see Figure 1b,c).

5.1. Mode of Failure and Crack Pattern

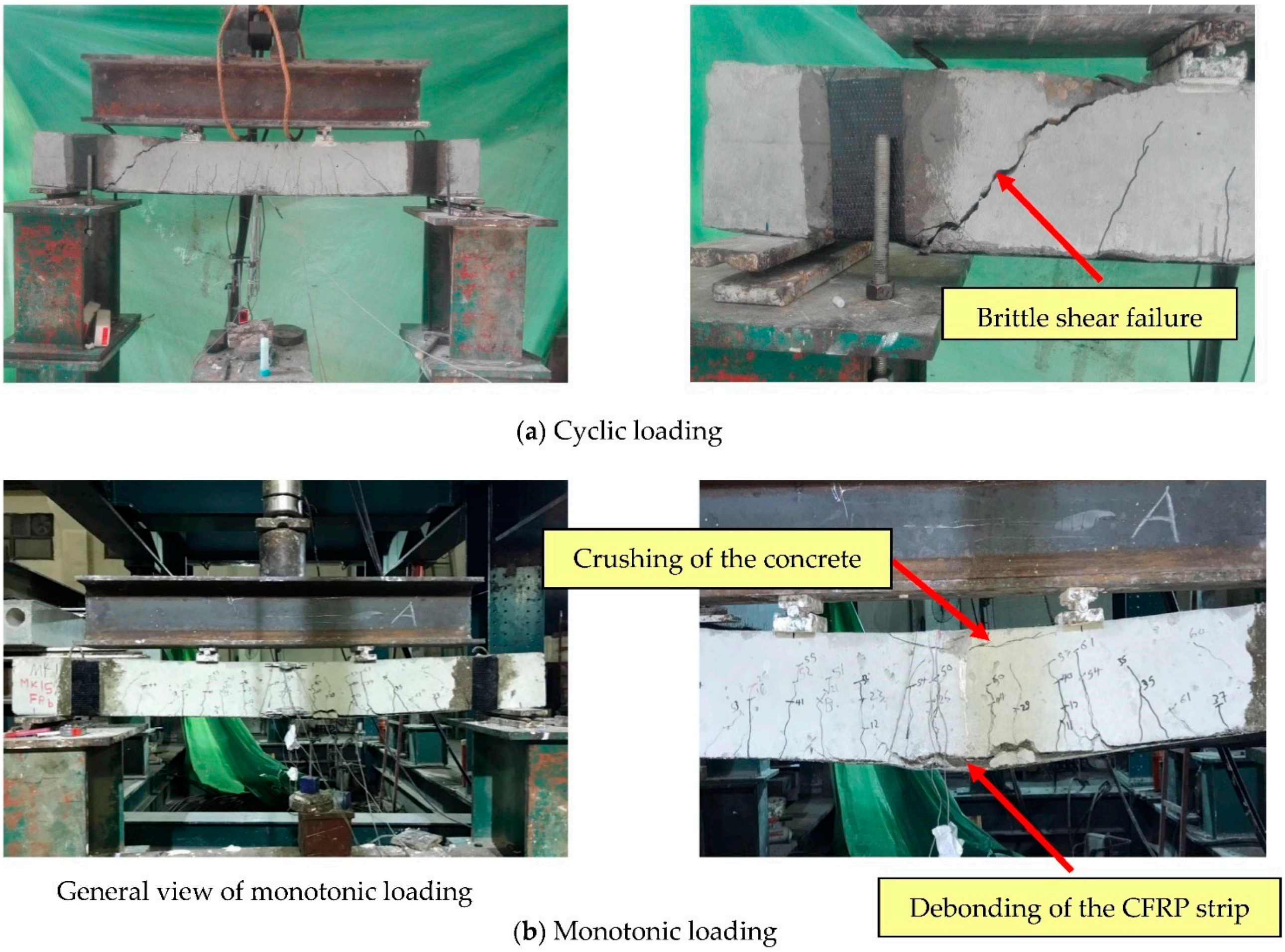
The tension of the pure bending at the bottom of the beam caused first vertical flexural crack at the middle third of the beam, while moving away from the middle third of the beam, diagonal cracks appeared as a result of the combined action of shear and bending moment. The behavior of the CFRP-strengthened specimen was significantly different. CFRP strengthening increased the beam's flexural capacity. Consequently, a brittle shear failure mechanism took place as seen in Figure 13a. This is also in contrast to the monotonic load, where concrete crushing at the mid-span occurred, as seen in Figure 13b. This might be related to the increase in the modulus of elasticity (E_d) as compared to the static one (E_c) and the increase in the post-yield stress of steel due to the effect of cyclic loading [40–42]. There is also another reason that cannot be ignored, which is the occurrence of debonding of the CFRP strip at mid-span, "the section of maximum moment", which abruptly decreased the capacity of the section causing such a failure pattern with the monotonic loading.

5.2. Load–Deflection Relationship

5.2.1. Comparison between Beams (MK15-CFRP) and (MK15) under Cyclic Loading

Figure 14 shows the load versus mid-span deflection curve for the MK15-CFRP and MK15 beams. For both beams, the first crack with progressive stiffness reduction was observed after the first cycle. Three cyclic loading groups were enough to get the bottom "tension" reinforcement to the yielding point for both beams, whereas the initial stiffness of the strengthened beam, in addition to the stiffness of the cracked section, was significantly higher. Accordingly, the ductility decreased by half the case of the non-strengthened beam. The results show that the strengthening technique increased the ultimate load by 1.9 times that of MK15; see Figure 14. Moreover, the flexural behavior of failure changed to brittle shear failure, where sudden failure was observed after reaching the ultimate load as previously mentioned; see Figures 13 and 14. This is because CFRP strengthening increased the beam's flexural capacity.

The strengthening decreased the dissipated energy by 28% as compared to the non-strengthened beam because the strengthening decreased the ductility as it clearly reduced the deformation ability of the beam. The results also indicate that the strengthening decreased the percentage of the stiffness at the last cycle to the initial one "%SL/SI" by 15% as compared to the non-strengthened beam. These observations are fully consistent with the results of the study carried out by Shrivastava et al. [35], which shows that FRP increased the flexural strength of beams and reduced the ductility as it showed catastrophic brittle failure.



(**a**) Cyclic loading

(**b**) Monotonic loading

Figure 13. Crack pattern for strengthened beams with CFRP strips.

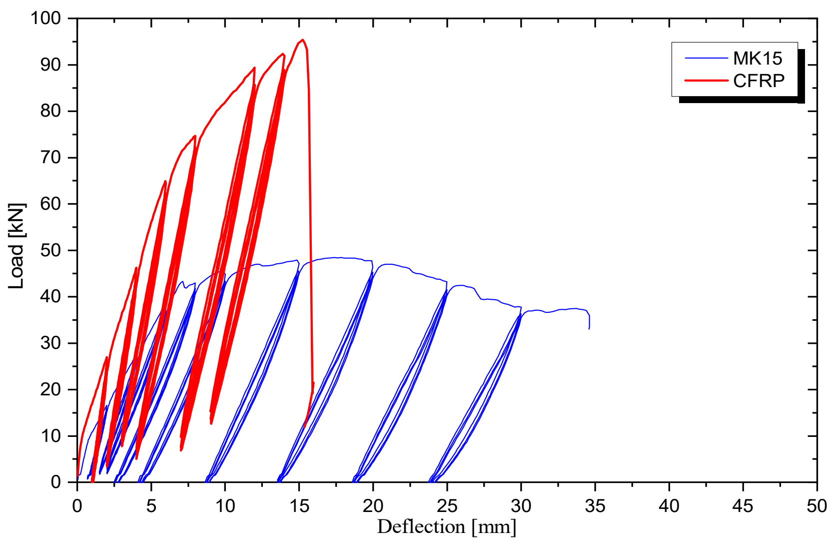


Figure 14. Load–deflection curve for CFRP-MK15 and MK15 beams under cyclic loading.

5.2.2. Comparison between Cyclic and Monotonic Loads for the Strengthened Beams

The behavior of failure for the CFRP-strengthened beam under cyclic loading showed brittle shear failure, where sudden failure occurred after reaching the ultimate load as previously mentioned; see Figure 13. The CFRP-strengthened beam under monotonic loading showed a relatively longer post-peak plateau; see Figure 15. The deformation ability and the ductility of the beam under monotonic loading increased by about 20%, as compared to the cyclic loading case. Moreover, the strengthened beam under cyclic loading shows an increase in both yielding and ultimate loads by 55% and 53%, respectively, as compared to the monotonic case. The reason might be that, during the cyclic loading condition, the loading and unloading process gives the beams the chance to redistribute the applied loads and close the formed cracks during the unloading stage. In addition to that, the increase in the modulus of elasticity (E_d) as compared to the static one (E_c) and the increase in the post-yield stress of steel due to the effect of cyclic loading [40–42] may also be factors. Consequently, the capacity of the section increased as previously mentioned. Moreover, it is worth mentioning that in the monotonic case at failure, debonding of the CFRP strip followed by concrete crushing at the top of the mid-span was observed. This may be an added reason to decrease the capacity of the beam in the monotonic load's case. The energy dissipation of the beam under cyclic loads was increased by about 62% as compared to the monotonic load case; see Figure 15.

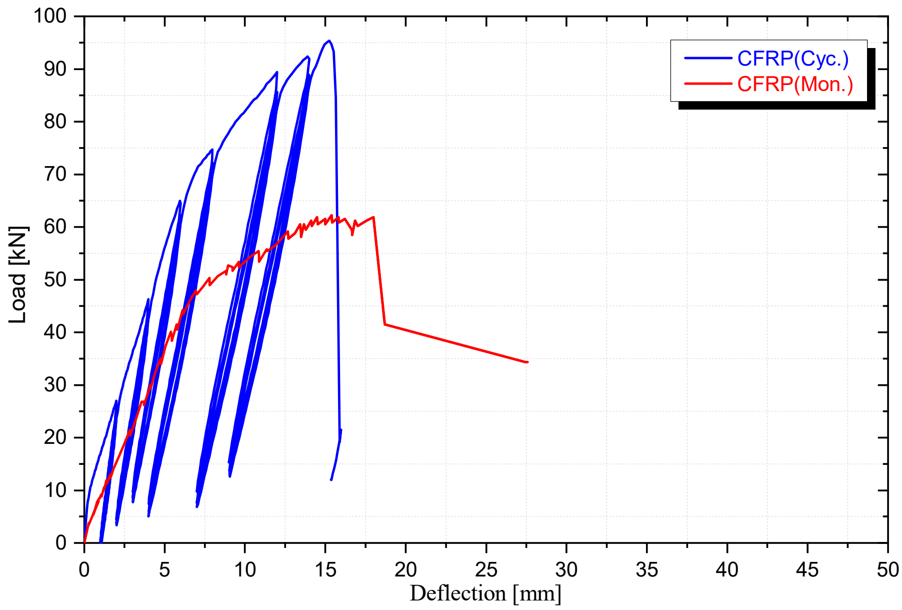


Figure 15. Load–deflection curve for the Strengthened beams with 15% replacement for monotonic and cyclic Loading.

6. Conclusions

In the present research, tests were performed on ten simply supported concrete beams of relatively large scale. The effect of using different percentage of metakaolin on the flexural behavior, ductility and energy dissipation of non-strengthened beams was studied. Moreover, CFRP strengthening of RC beams with metakaolin replacement was also explored. Cyclic and monotonic displacement-controlled loading protocols were used in all beams. Based on the results of the experiments, the following conclusions can be drawn:

Metakaolin as cement replacement can be used up to 20% without a negative effect on the behavior of RC beams under cyclic or monotonic loading protocols.

Flexural failure is the dominant failure mechanism of non-strengthened beams under both cyclic and monotonic loading protocols regardless of the percentage of cement replacement.

The percentage of energy dissipation for beams with metakaolin replacement is influenced by the type of loading. Compared to the control RC beam, energy dissipation increased under cyclic loading, while it decreased under monotonic loading.

The percentage of cement replacement did not affect either the maximum or the ultimate loads under the effect of cyclic loading.

The ductility was not negatively affected by the percentage of metakaolin replacement; rather, some improvement was observed.

For cyclic loading, CFRP strengthening increased the ultimate load of the beams significantly. Moreover, it changed the flexural failure mechanism of the non-strengthened beam to brittle shear failure.

For the strengthened beam, the crack patterns and failure modes differed according to the loading protocol. Brittle shear failure occurred under the cyclic loading, while under the monotonic loading, debonding of the CFRP strip occurred followed by crushing of the concrete at the mid-span.

The obtained results are limited to the scale of the tested specimens. Moreover, other specimens with higher percentages of metakaolin replacement can be tested.

Author Contributions: Conceptualization, H.E., A.M.R.M., K.A.e.-h. and A.S.; methodology, H.E., A.M.R.M. and A.S., experimental and testing H.E., A.M.R.M. and K.A.e.-h.; Validation, H.E. and A.S.; investigation, H.E. and A.S.; data curation, H.E., A.M.R.M. and A.S.; writing—original draft preparation H.E., A.M.R.M. and K.A.e.-h.; review and editing, A.S.; Visualization, H.E. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data used are included in the study.

Acknowledgments: The experimental work was carried out using the facilities of the "Central Research Unit for Engineering Materials", Delta University for Science and Technology and the "Reinforced Concrete and Heavy Structures Lab", Faculty of Engineering, Tanta University.

Conflicts of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Lehne, J.; Preston, F. Making Concrete Change Innovation in Low-carbon Cement and Concrete. In *Energy, Environment and Resources Department, Chatham House Report*; The Royal Institute of International Affairs: Cambridge, UK, 2018.
2. Patil, B.B.; Kumbhar, P.D. Strength and durability properties of High Performance Concrete incorporating high reactivity Metakaolin. *Int. J. Mod. Eng. Res.* **2012**, *3*, 1099–1104.
3. Issac, S.; Paul, A. A Literature Review on the Effect of Metakaolin and Fly Ash on Strength Characteristics of Concrete. *Int. J. Adv. Res. Innov. Ideas Educ.* **2018**, *2*, 55–60.
4. Aiswarya, S.; Prince Arulraj, G.; Dilip, C. A Review on use of Metakaolin in concrete. *Eng. Sci. Technol. Int. J.* **2013**, *3*, 592–597.
5. Sreenivasalu, A.; Srinivasa Rao, K. Design of M100 grade concrete (ACI method). *Glob. J. Eng. Appl. Sci.* **2012**, *2*, 183–185.
6. Dubey, S.; Chandak, R.; Yadav, R.K. Effect of Metakaolin on Compressive Strength of Concrete. *Int. J. Eng. Res. Appl.* **2015**, *5*, 80–82.
7. Alharbi, Y.R.; Abadel, A.A.; Mayhoub, O.A.; Kohail, M. Effect of using available metakaoline and nano materials on the behavior of reactive powder concrete. *Constr. Build. Mater.* **2021**, *269*, 121344. [CrossRef]
8. Weise, K.; Ukrainczyk, N.; Duncan, A.; Koenders, E. Enhanced Metakaolin Reactivity in Blended Cement with Additional Calcium Hydroxide. *Materials* **2022**, *15*, 367. [CrossRef]
9. Srivastava, V.; Kumar, R.; Agarwal, V.C.; Mehta, P.K. Vikas Effect of Silica Fume and Metakaolin combination on concrete. *Int. J. Civ. Struct. Eng.* **2012**, 893–900. [CrossRef]
10. Muralinathan, P.; Daniel, A.J.; Sivakamasundari, S. Study of High Strength Concrete Using Metakaolinat Elevated Temperatures. *Int. J. Pure Appl. Math.* **2018**, *119*, 1267–1273.
11. Saboo, N.; Shivhare, S.; Kori, K.K.; Chandrappa, A.K. Effect of Fly Ash and Metakaolin on Pervious Concrete Properties. *Constr. Build. Mater.* **2019**, *223*, 322–328. [CrossRef]
12. Supit, S.W.M.; Pandei, R.W. Effects of metakaolin on compressive strength and permeability properties of pervious cement concrete. *J. Teknol.* **2019**, 33–39. [CrossRef]
13. Akhtar, A.; Aqil, T. Effect on Flexural Strength by using Glass Fibre and Metakaolin in Concrete. *Int. J. Res. Appl. Sci. Eng. Technol.* **2017**, 322–326.
14. Jagtap, S.A.; Shirsath, M.N.; Karpe, S.L. Effect of Metakaolin on the Properties of Concrete. *Int. Res. J. Eng. Technol.* **2017**, *4*, 643–645.

15. Rashwan, M.M.; Megahed, A.R.; Essa, M.S. Effect of local metakaolin on properties of concrete and its sulphuric acid resistance. *JES J. Eng. Sci.* **2015**, *43*, 183–199. [CrossRef]
16. Sarangi, P.; Panda, K.C.; Jena, S. Effect of Metakaolin on the Enhancement of Concrete Strength. *Indian J. Sci. Res.* **2017**, *14*, 121–127.
17. Patil, S.P.; Sangle, K.K. Flexural Strength Evaluation of Prestressed Concrete Beams with Partial Replacement of Cement by Metakaolin and Flyash. *Am. Int. J. Res. Sci. Technol. Eng. Math.* **2013**, *3*, 187–194.
18. Dennison, D.; Simon, J.M. Effect of Metakaolin on the Structural Behavior of Normal and Steel Fiber Reinforced Concrete Beams. *Int. J. Sci. Eng. Res.* **2014**, *5*, 1684–2278.
19. Sherif, M.A. Utilization of Metakaolin on Sustainable Concrete Properties. *IOSR J. Mech. Civ. Eng.* **2017**, 61–71.
20. Ding, J.T.; Li, Z. Effects of Metakaolin and Silica Fume on Properties of Concrete. *ACI Mater. J.* **2002**, *99*, 393–398.
21. Bashir, I.A.; Rasool, M.A.; Rashid, M.; Singh, P. Experimental Investigation of Compressive Behaviour of Pier by Partial Replacement of Metakaolin. *Glob. J. Technol. Optim.* **2017**, *8*, 22–28. [CrossRef]
22. Chalioris, C.E.; Kosmidou, P.-M.K.; Karayannis, C.G. Cyclic Response of Steel Fiber Reinforced Concrete Slender Beams: An Experimental Study. *Materials* **2019**, *12*, 1398. [CrossRef] [PubMed]
23. Zhu, H.; Li, C.; Cheng, S.; Yuan, J. Flexural Performance of Concrete Beams Reinforced with Continuous FRP Bars and Discrete Steel Fibers under Cyclic Loads. *Polymers* **2022**, *14*, 1399. [CrossRef]
24. Hyun, J.-H.; Bang, J.-W.; Lee, B.-Y.; Kim, Y.-Y. Effects of the Replacement Length of Concrete with ECC on the Cyclic Behavior of Reinforced Concrete Columns. *Materials* **2021**, *14*, 3542. [CrossRef]
25. Wang, H.; Wu, Y.; Wei, M.; Wang, L.; Cheng, B. Hysteretic Behavior of Geopolymer Concrete with Active Confinement Subjected to Monotonic and Cyclic Axial Compression: An Experimental Study. *Materials* **2020**, *13*, 3997. [CrossRef] [PubMed]
26. Xiao, S.; Li, J.; Mo, Y. Effect of loading rate on cyclic behavior of reinforced concrete beams. *Adv. Struct. Eng.* **2018**, *21*, 990–1001. [CrossRef]
27. Shankar, G.R.V.; Suji, D. Static and cyclic behaviour of high performance concrete beams using Metakaoline and partial replacement with quarry dust. *J. Ind. Pollut. Control.* **2014**, *30*, 153–162.
28. Lotfy, E.M. Flexural strengthening of R.C. Beams. *Int. J. Eng. Tech. Res.* **2016**, *6*, 83–86.
29. Mashrei, M.A.; Makki, J.S.; Sultan, A.A. Flexural Strengthening of Reinforced Concrete Beams Using Carbon Fiber Reinforced Polymer (CFRP) Sheets with Grooves. *Lat. Am. J. Solids Struct.* **2019**, *16*, e176. [CrossRef]
30. Mobin, M.N.; Hoque, M.M. Flexural Strengthening of RC Beams with Near Surface Mounted Reinforcing Steel Bars. *DUET J. Dhaka Univ. Eng. Technol.* **2018**, 1–10.
31. Moubarak, A.; Elwardany, H.; Abu Elhassan, K.; Taher, S. Optimizing metakaolin and Silica-fume in RC beams with/without strengthening. *Innov. Infrastruct. Solut.* **2021**, *6*, 117. [CrossRef]
32. Tarigan, J.; Patra, F.M.; Sitorus, T. Flexural strength using Steel Plate, Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) on reinforced concrete beam in building technology. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *126*, 012025. [CrossRef]
33. Salih, R.; Zhou, F.; Abbas, N.; Mastoi, A.K. Experimental Investigation of Reinforced Concrete Beam with Openings Strengthened Using FRP Sheets under Cyclic Load. *Materials* **2020**, *13*, 3127. [CrossRef] [PubMed]
34. Zhang, Y.; Nehdi, M.L. Experimental and Analytical Investigation on Flexural Retrofitting of RC T-Section Beams Using CFRP Sheets. *Appl. Sci.* **2020**, *10*, 1233. [CrossRef]
35. Shrivastava, R.; Gupta, U.; Choubey, U.B. Effect of cyclic loading on flexural behavior of FRP strengthened RC beams: A Stability Point Approach. *Int. J. Adv. Res. Eng. Appl. Sci.* **2013**, 9–26.
36. Sagar, R.V. Acoustic emission characteristics of reinforced concrete beams with varying percentage of tension steel reinforcement under flexural loading. *Case Stud. Constr. Mater.* **2017**, *6*, 162–176. [CrossRef]
37. NEHRP. *Recommended Seismic Provisions for New Buildings and Other Structures. FEMA P-1050-1, 2015 Ed.*; NEHRP, Building Seismic Safety Council, A Council of the National Institute of Building Sciences: Washington, DC, USA, 2015; Volume I: Part 1 Provisions, Chapter 14.
38. *ASTM C33/C33M-13*; Standard Specification for Concrete Aggregates. Annual Book of American Society for Testing and Materials ASTM: West Conshohocken, PA, USA, 2018.
39. Sika, Technical Data Sheet, Sikament 163 M, April 2018, Sika Egypt for Construction Chemicals, El Abour City, 1st Industrial Zone (A) Section # 10 Block 13035, Egypt. Available online: https://egy.sika.com/content/dam/dms/eg01/e/Sikament%C2%AE%20-163.pdf (accessed on 20 May 2022).
40. Kaufmann, E.J.; Metrovich, B.R.; Pense, A.W. *Characterization of Cyclic Inelastic Strain Behavior on Properties of A572 Gr. 50 and A913 Gr. 50 Rolled Sections*; ATLSS Report No. 01–13; Lehigh University: Bethlehem, PA, USA; American Institute of Steel Construction: Chicago, IL, USA, 2001.
41. Neville, A.M. *Properties of Concrete*, 4th ed.; Pearson Education Limited: Edinburgh Gate, UK, 2009; ISBN 978-0-582-23070-5.
42. Lee, B.J.; Kee, S.-H.; Oh, T.; Kim, Y.-Y. Evaluating the Dynamic Elastic Modulus of Concrete Using Shear-Wave Velocity Measurements. *Adv. Mater. Sci. Eng.* **2017**, *2017*, 1651753. [CrossRef]
43. Afefy, H.; Fawzy, T.M. Strengthening of RC one-way slabs including cut-out using different techniques. *Eng. Struct.* **2013**, *57*, 23–36. [CrossRef]