Mechanical Properties of High Strength Mortars Made with Fine Waste Concrete Aggregates and Ground Granulated Blast Furnace Slag

Ali Hassoon Nahhab
Department of Civil Engineering, University of Babylon, Babylon, Iraq
eng.ali.hasson@uobabylon.edu.iq
alinahhab@yahoo.com

Abstract

The mechanical properties of high strength mortars produced with fine waste concrete aggregate (FWCA) and GGBFS were investigated. The natural sand was replaced by FWCA with different levels, namely 0, 25, 50, 75, and 100%. The ordinary Portland cement (OPC) was substituted by GGBFS with 0, 30, and 60% by weight. To satisfy the requirements of high strength, all the mortar mixes were made with a 0.25 w/b ratio. The hardened mortars were tested for compressive strength, splitting tension, and fracture parameters at different ages. The experimental findings showed that the mixtures with FWCA showed lower strength, fracture energy and toughness compared to the corresponding reference mixes at a given age and GGBFS content. The 30% replacement of OPC by GGBFS improved the strengths of all mixes at 28 and 90 days. Moreover, the use of 30% GGBFS counterbalanced the strength decrement due to the use of the FWCA such that the mixtures with FWCA and GGBFS showed strengths comparable to or even exceeded the strengths of the mixtures made with natural sand only.

Keywords: Fine waste concrete aggregate (FWCA); High strength mortars; Slag; Tensile strength; Fracture energy; Toughness.

الخلاصة

تم خلال هذا البحث دراسة الخواص الميكانيكية للمونة عالية المقاومة المنتجة من ركام مخلفات الخرسانة ومطحون خبث الفرن النفاخ. استبدل الركام الناعم الطبيعي بركام مخلفات الخرسانة بنسب مختلفة هي 0، 0.25، 0.5،0.75 و 100%. استبدل السمنت البورتلاندي الاعتيادي بنسب مختلفة من مطحون الخبث هي 0،30 و60%. كانت نسبة الماء الى المادة الرابطة هي 0.25 لتحقيق متطلبات المقاومة العالية. تم اجراء فحوصات مقاومة الانضغاط والشد الانشطاري ومعاملات الكسر على المونة المتصلبة باعمار مختلفة. بينت النتائج المختبرية بان الخلطات الحاوية على ركام مخلفات الخرسانة قد ابدت مقاومة وطاقة كسر وصلادة اقل من الخلطات المرجعية عند تثبيت نسبة مطحون الخبث. كما ان استخدام مطحون الخبث بنسبة 30% قد حسن المقاومة لجميع الخلطات في الاعمار 28 و 90 يوم. بالإضافة الى ذلك فان استعمال تلك النسبة من مطحون الخبث قد قلل من او ازال تماما التأثير السلبي لركام مخلفات الخرسانة بحيث ان الخلطات الحاوية على مطحون الخبث وركام مخلفات الخرسانة قد ابدت مقاومة مماثلة او حتى اعلى من تلك الحاوية على الركام الطبيعي فقط.

الكلمات المفتاحية: ركام مخلفات الخرسانة، المونة عالية المقاومة، الخبث، مقاومة الشد، طاقة الكسر، الصلادة.

1. Introduction

The demand of building materials like concrete have been growing considerably because concrete is essential for many construction works such as buildings, bridges, and highways. So, these construction works need large amounts of natural aggregate, which leads to the scarcity of natural aggregate resources. Moreover, many infrastructures and buildings have been destroyed by the action of wars or their service life has reached the end. This increases the quantity of demolition and construction waste appreciably.

Though there are very large quantitates of demolition as well as construction waste, only a small portion is reused in the production of cement-based materials. In EU, for example, among of about 450 million tons of waste, only 28% is recycled and the rest is disposal (Bui *et.al.*, 2017). The disposal of demolition and construction waste materials causes the health hazard and environmental problem.

Production of waste concrete aggregate seems as an encouraging way to recycle some of waste. However, the physical and mechanical characterizations of recycled aggregate may be poorer than those of natural aggregate because of the presence of the remaining mortar on a recycled particle which comparatively has high porosity and less strength (Kanish *et.al.,* 2016). This may cause the strength and durability properties to reduce for concrete made with waste concrete aggregates compared to that made with natural sand. The situation may become more complicated in the case of concrete or mortar of high strength as the recycled aggregate contributes to the strength of the composite. It is accepted that the aggregate strength does not have an appreciable effect on the strength of normal strength concrete because it is stronger than cement paste. However, this is not the case with high strength concrete where the strength of aggregate becomes of importance.

Recently, there has been an increasing use of binary bends of Portland cement and GGBFS in concrete and mortar mixtures. The pozzolanic nature of GGBFS reduces the porosity of cement paste, decreases the size of pores, and decreases the mobility of chloride ions (Song and Saraswathy, 2006).

The previous studies generally showed that using waste concrete aggregate in concrete mixtures led to decline the properties of concrete, including strength, toughness, and elastic modulus (Poon *et.al.,* 2004; Xiao *et.al.,* 2005; Etxeberria *et.al.,* 2007; Chakradhara Rao et al., 2011). Many researchers, including (Topçu and Günçan, 1995; Xiao *et.al.,* 2005) concluded that increasing the replacement level diminished the concrete strength. However, a few researches drew opposite conclusion (Ho *et.al.,* 2013). This contradiction may be due to the variation in (1) the moisture condition of recycled coarse aggregates, (2) the loss in the quality of recycled coarse aggregates which depends on their specific gravity, and (3) the quantity of old mortars adhered on the particle surface (Zhou and Chen, 2017). Nevertheless, the use of supplementary cementitious materials seems to be a visible solution to compensate for the low strength of the mixtures prepared with waste concrete aggregate. A study by (Corinaldesi and Moriconi, 2009) indicated that the compressive strength of concrete made with waste concrete aggregate was equal to or even higher than the strength of natural aggregate concrete because of partial replacing recycled fine aggregate by class F fly ash or silica fume.

Similar to concrete, mortars produced with recycled fine aggregate generally show a lesser strength and durability as compared to those made with natural fine aggregate (Corinaldesi, 2009; Choi *et.al.,* 2009; Lee *et.al.,* 2012). In general, the mortar exhibits a drop in compressive strength with rising the percentage of recycled aggregate. On the other hand, as with concrete, a few researchers concluded that the use of this type of aggregate does not alter the mortar characteristics appreciably whenever the content of recycled aggregate is 30% or less (Barga *et.al.,* 2012; Vegas *et.al.,* 2009).

2. Research Significance

Though many studies focused on the normal strength concretes and Portland cement mortars produced with waste concrete aggregate, the available data is very limited regarding high strength cementitious mortars made with this type of recycled aggregate and supplementary cementitious materials like GGBFS. So, this study examined the mechanical characteristics of high strength mortars made with various levels of FWCA and GGBFS.

3. Experimental Program

3.1. Raw Materials

3.1.1. Cement (OPC) and Slag (GGBFS)

Tables 1 and 2 present the characterizations of the OPC and GGBFS utilized in the current research.

Table 1: Chemical properties of OPC and GGBFS

Chemical composition	OPC	GGBFS
SiO_2 (%)	20.15	38.42
Al_2O_3 (%)	5.26	11.6
Fe_2O_3 (%)	3.98	1.14
CaO (%)	62.10	35.27
MgO (%)	1.91	7.43
SO_3 (%)	2.48	0.72
K_2O (%)	0.91	–
Na_2O (%)	0.16	–
Loss on ignition (%)	2.85	–
Insoluble residue (%)	0.14	–

Table 2: Physical properties of OPC and GGBFS

Item	OPC	GGBFS
Specific gravity	3.15	2.9
Fineness (cm^2/g)	3620	5650
Expansion (%)	0.32	-
Initial setting time (min)	208	-
Final setting time (min)	285	-

3.1.2. Fine Aggregate

Two types of fine aggregates were utilized in the present investigation: natural fine aggregate (NFA) and fine waste concrete aggregate (FWCA). In order to get FWCA, a concrete mix with a 20 MPa target compressive strength was prepared and poured into 15 cm cubic molds. After curing, the cubes were crushed by using Los Angeles abrasion machine. Then FWCA was graded in terms of portions to provide the grading similar to the NFA. The gradation curves of NFA and FWCA are illustrated in Figure 1. The gradation of both types of aggregates was in accordance with (IQS No. 45/1984). The specific gravity of NFA and FWCA was 2.65 and 2.3, respectively. The values of water absorption were 0.61% for NFA and 10.3% for FWCA.

3.1.3. Superplasticizer

In order to obtain the required w/b ratio and flowability, superplasticizer was used in both natural aggregate and recycled aggregate mortar mixtures. This chemical admixture was classified as type F according to ASTM C 494.

3.2. Mortar Mixture Proportions

As shown in Table 3, a total number of 15 mixes of mortars were prepared in the present work. The first 5 mixes were prepared without GGBFS. In this group of mixes, the NFA was replaced by different percentages of FWCA, namely 0, 25, 50, 75, and 100%. In the second and third group of mixes, 30% and 60% of OPC had been substituted by GGBFS, respectively and the same previous FWCA levels were adopted. The w/b ratio of all groups was kept constant at 0.25.

3.3. Preparation and Curing of Samples

In the literature, different mixing procedures for high strength mortars were adopted (Yazici, 2007). However, the general conclusion derived from the previous studies is that the mixing time of these mixes exceeds that of conventional mortars. This is necessary to ensure the required homogeneity and flowability of the mixes in which a high binder level is used. The mortar mixes were mixed by Hobart mixer. Figure 2 shows the procedure of mixing. All hardened mortar specimens were cured in water until the testing age.

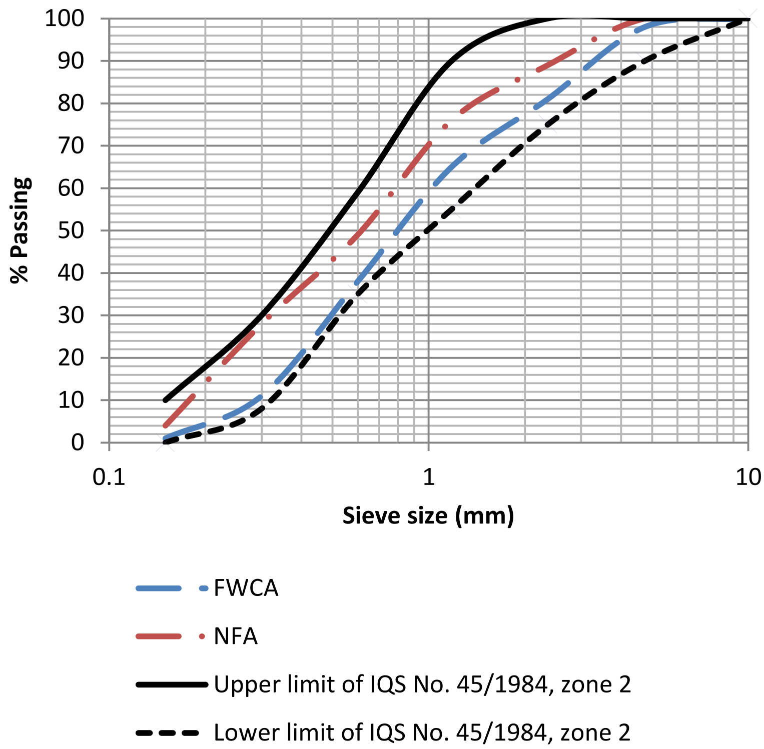


Figure 1: Distribution of particle size of the fine aggregate.

3.4. Testing Methods

3.4.1. Flow Test

The flow test measures the consistency of the mortars. The test procedure was performed according to ASTM C230/C230M. The flow diameter of the sample was calculated as the average of the two perpendicular diameters. By using an appropriate amount of superplasticizer, the flow diameter was kept constant for all mixes at 200 ± 10 mm.

3.4.2. Compressive Strength

The compressive strength test was performed on the cubes of 50*50*50 mm at various ages of 7, 28, and 90 days. The test method was done in accordance with ASTM C 109/C 109M.

3.4.3. Splitting Tensile Strength

At 7, 28, and 90 days, the indirect tensile strength test was conducted on 50 mm cubes following the procedure outlined in BS 1881: Part 111. The procedure for the indirect tensile strength test is illustrated in Plate 1. The splitting tensile strength is calculated as:

$$f_{sp} = \frac{2p}{\pi a^2} \tag{1}$$

Where p is the maximum load and a is the side length of the cube.

Table 3: Mix proportion of Mortars.

Mix code	Mix description	OPC	GGBFS	NFA*	FWCA**	Water	SP***
N100R0G0	100% NFA+ 0% FWCA + 0% GGBFS	700	0	1550	0	175	18
N75R25G0	75% NFA+ 25% FWCA + 0% GGBFS	700	0	1162.5	387.5	175	20
N50R50G0	50% NFA+ 50% FWCA + 0% GGBFS	700	0	775	775	175	21
N25R75G0	25% NFA+ 75% FWCA + 0% GGBFS	700	0	387.5	1162.5	175	25
N0R100G0	0% NFA+ 100% FWCA + 0% GGBFS	700	0	0	1550	175	28
N100R0G30	100% NFA+ 0% FWCA + 30% GGBFS	490	210	1535	0	175	16
N75R25G30	75% NFA+ 25% FWCA + 30% GGBFS	490	210	1151	384	175	18
N50R50G30	50% NFA+ 50% FWCA + 30% GGBFS	490	210	767.5	767.5	175	18
N25R75G30	25% NFA+ 75% FWCA + 30% GGBFS	490	210	384	1151	175	20
N0R100G30	0% NFA+ 100% FWCA + 30% GGBFS	490	210	0	1535	175	20
N100R0G60	100% NFA+ 0% RFA + 60% GGBFS	280	420	1519	0	175	16
N75R25G60	75% NFA+ 25% FWCA + 60% GGBFS	280	420	1139	380	175	18
N50R50G60	50% NFA+ 50% RFA + 60% GGBFS	280	420	759.5	759.5	175	18
N25R75G60	25% NFA+ 75% FWCA + 60% GGBFS	280	420	380	1139	175	20
N0R100G60	0% NFA+ 100% FWCA + 60% GGBFS	280	420	0	1519	175	20

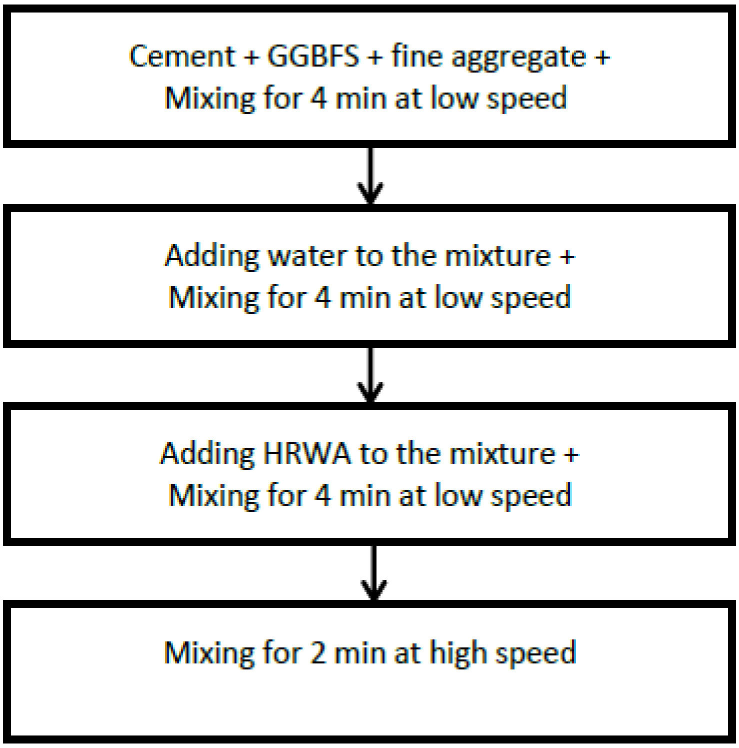


Figure 2: Mixing procedure for mortars.

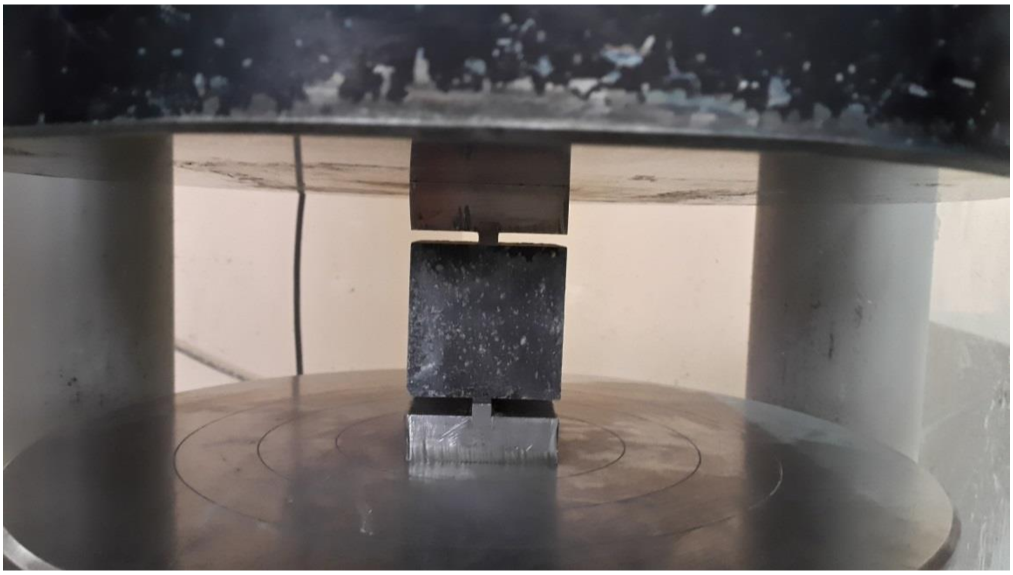


Plate 1: Procedure for splitting tension test.

3.4.4. Fracture Parameters

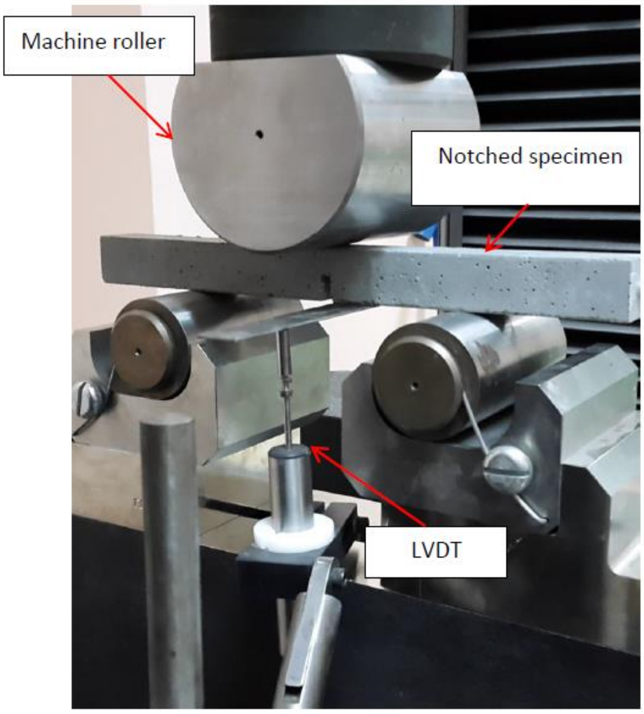
In this study, the investigated fracture parameters were fracture energy, G_f, toughness, and net flexural strength. The fracture energy and toughness were determined according to the (RILEM 50-FMC). For this purpose, notched prisms of 25*25*285 mm with a span of 150 mm were tested under center-point bending by using a computerized testing machine (Plate 2). The rating load was 0.01 mm/min. The fracture energy is calculated as:

$$G_F = \frac{A + w\delta_{l}^{s}}{b(d-a)} \qquad (2)$$

Where A is the area under the load displacement plot up to 0.4 mm, w is the weight of the prism, δ is the displacement for the prism; S and L are the span and length of the prism; b, d, and a are width, height and notched depth of the prism, respectively.

The net flexural strength, f_{flex}, is calculated as:

$$f_{flex} = \frac{3\,PS}{2b(d-a)^2} \quad (3)$$



(a) (b)

Plate 2: Flexural test procedure (a) Testing machine (b) Notched beam under three point bending.

4. Results and Discussion

4.1. Compressive Strength

Figures 3-5 give the relation between compressive strength of mortars and the FWCA content for different ages. As seen in Figure 4, the 28-day compressive strength of mortars was varied between about 55 and 75 MPa. This suggests that all the mortars can be classified as high strength mortars. Increasing the FWCA percentage diminished the compressive strength of mortars irrespective of age and GGBFS level. With respect to the control mixes (without FWCA), there was a compressive strength reduction of 2-14% depending on the FWCA content. Zhao et al., 2015 reported that the compressive strength of Portland cement mortar made with different w/c ratios ranging from 0.5 to 0.6 has decreased by about 30% due to the replacement of calcareous aggregate by FWCA.

The FWCA particle is typically surrounded by porous and soft residual mortar which weakens the bond between aggregate and cement paste. The relatively lower strength of high strength mortars made with FWCA could be, therefore, related to the inferior properties of FWCA as compared to NFA.

When the effect of GGBFS was considered, the inclusion of GGBFS decreased the 7-day compressive strength of mortars (Figure 3). This was observed whatever the FWCA content. However, at later ages, namely 28 and 90 days, the compressive strength of all mixes enhanced as the GGBFS content was improved up to a certain percentage beyond which the strength initiated to slow down. The GGBFS content of 30% was the optimum percentage at which the maximum compressive strength was obtained at 28 and 90 days. At these ages, the strength reduction due to the presence of FWCA was generally compensated by the addition of 30% GGBFS though the positive effect of GGBFS was more pronounced at the end of curing period (90 days) . In other words, the strengths of recycled aggregate mortars with 30% GGBFS were comparable to or even higher than those of normal aggregate without GGBFS at a given age . At 28 days, the compressive strength of natural aggregate mortar without GGBFS (N100R0G0) was 69.8 MPa while the strength of recycled aggregate mortars with 30% GGBFS and FWCA contents of 25, 50, 75 and 100% was 74.5, 70.3, 69.5, and 68.3 MPa, respectively. At the age of 90 days, the mortars containing 30% GGBFS and FWCA showed compressive strengths of 77.4 to 85 MPa.

At early ages, hydration of GGBFS is very slow and as age progresses, the activation of GGBFS takes places. The ongoing release of alkalis by GGBFS together with the CH formation by Portland cement leads to the progressive pozzolanic reaction over a long period (Neville, 2000). Such reaction produces mortars with denser microstructure and more strength than the ordinary Portland cement mortars.

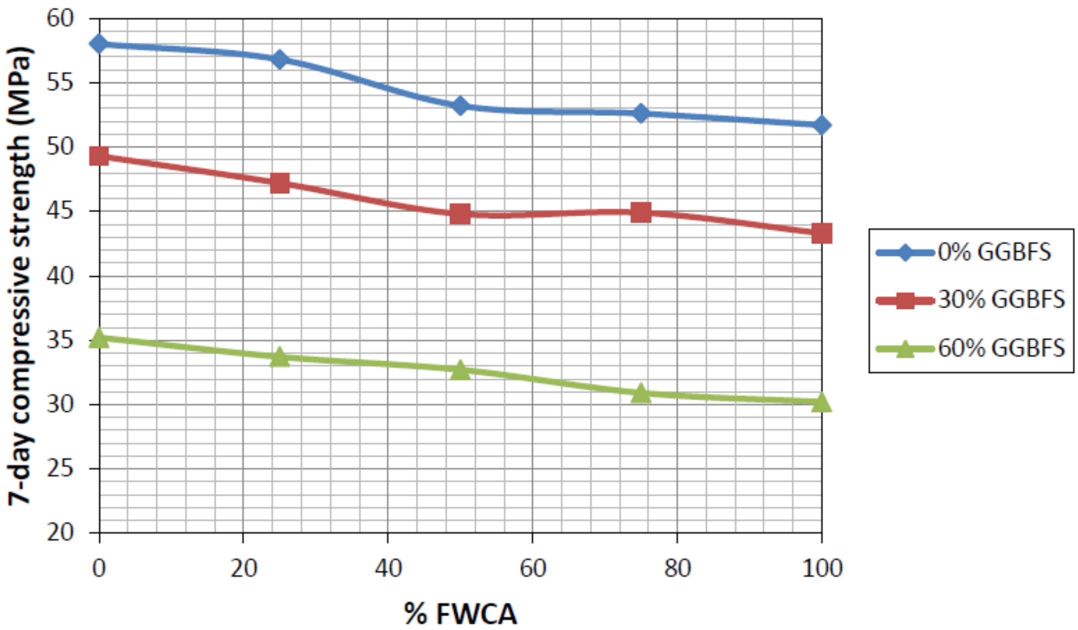


Figure 3: Compressive strength of the high strength mortars at 7 days.

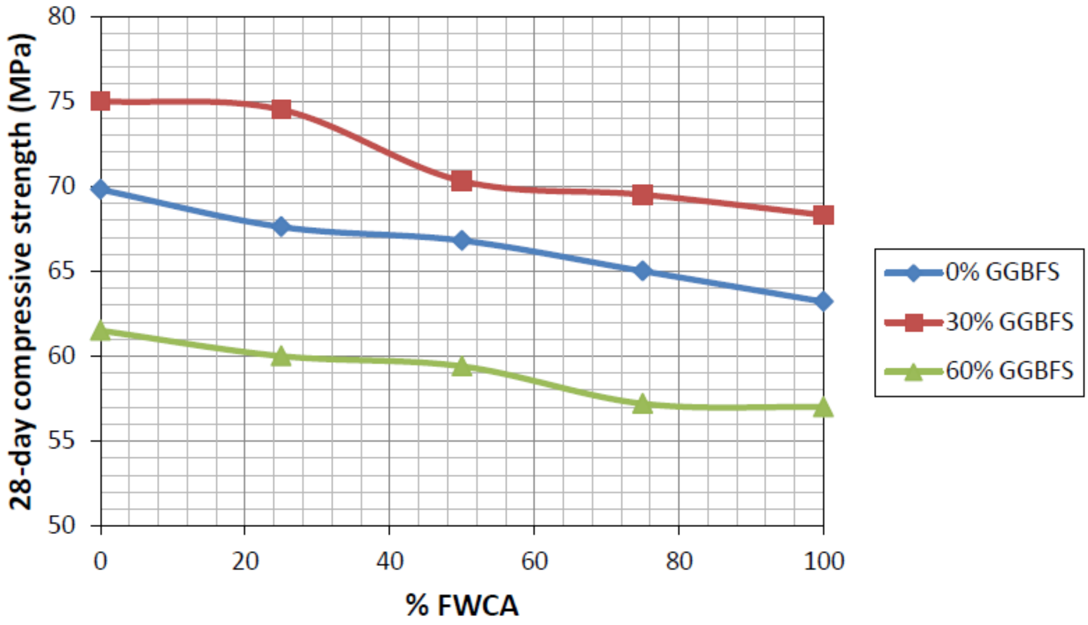


Figure 4: Compressive strength of the high strength mortars at 28 days.

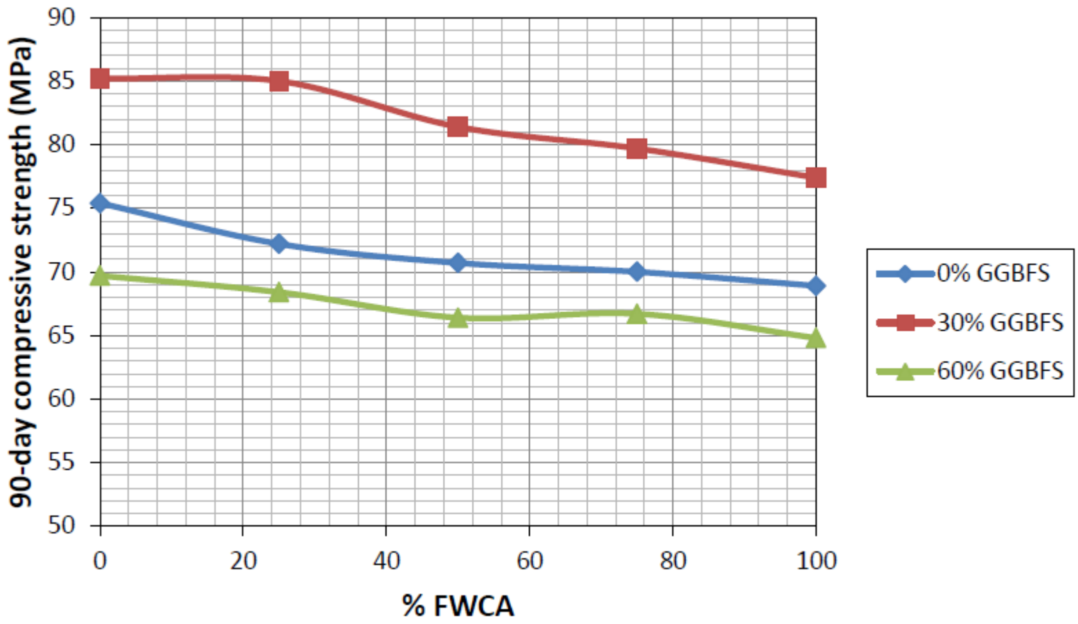


Figure 5: Compressive strength of the high strength mortars at 90 days.

4.2. Splitting Tensile Strength

The effect of FWCA percentage on the indirect tensile strength of mortars at various ages is presented in Figures 6-8. The effect of GGBFS was also shown in these figures. It is obvious from these figures that the mixes made with FWCA showed lower indirect tensile strength than those made with NFA mixes regardless of the age and GGBFS content. The drop in splitting tensile strength was varied between 2 and 17%, depending on the content of FWCA in the mixtures.

The opposite relation between the FWCA and indirect tensile strength may be related the poor quality of the old mortar adhered to the FWCA particles. This declines the properties of interfacial transition zone, thus decreasing the tensile strength of mortar. Nevertheless, the angular shape of FWCA resulted in a good mechanical interlocking of aggregates thus making the reduction not much significant particularly at a relatively low FWCA content (up to 50%).

As with the compressive strength, the 7-day indirect tensile strength was lower with increasing GGBFS content regardless of the FWCA content due to the slow hydration of GGBFS. Beyond the age of 7 days, the splitting tensile strength was higher at 30% GGBFS and lower at 60% GGBFS as compared to that of the mixes without GGBFS. At 28 days, for instance, the replacement of 30% OPC by GGBFS resulted in an increase in splitting tensile strength of 11-19%.

At later ages (28 and 90 days), the mixes incorporating GGBFS became denser than the mixes not containing it due to less portlandite and more calcium silicate hydrates. The inclusion of 30% GGBFS compensated the reduction in splitting tensile strength caused by the use of FWCA and the effect of this type of mineral admixture was more obvious at 90 days. For instance, the reference mix (N100R0G0) recorded a splitting tensile strength of 6.15 MPa at 90 days while the values of 6.93, 6.72, 6.50, and 6.21 MPa were recorded for mixes (N75R25G30), (N50R50G30) (N25R75G30), and (N0R100G30), respectively. In other words, the tensile strength of mortars with FWCA and 30% GGBFS exceeded that of mortars with only NFA at the end of curing time. Such behavior may be related to the enhanced ITZ caused by the incorporation of a pozzolanic material like GGBFS.

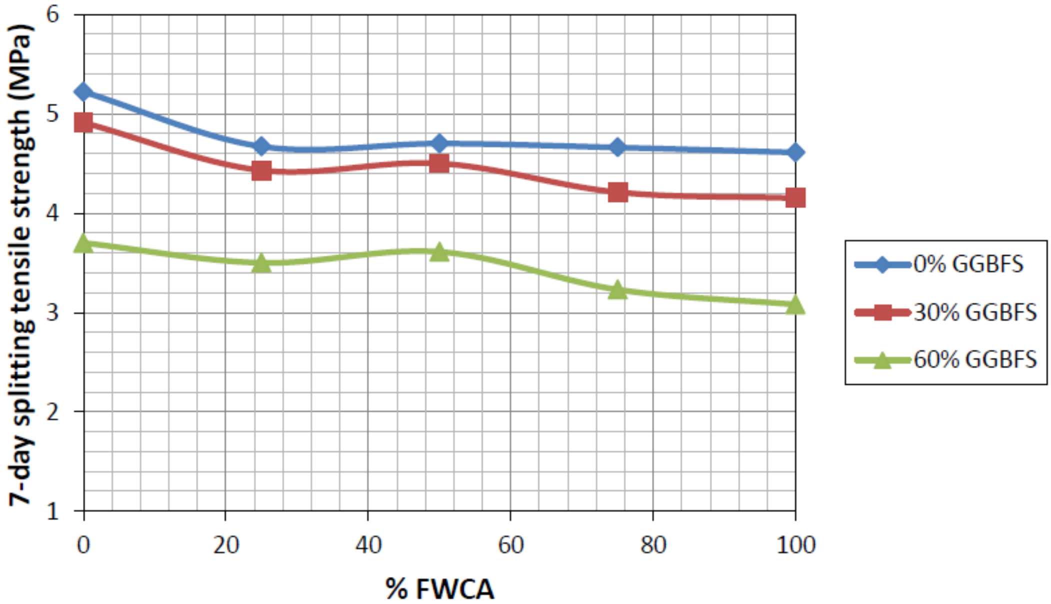


Figure 6: Indirect tensile strength of the high strength mortars at 7 days.

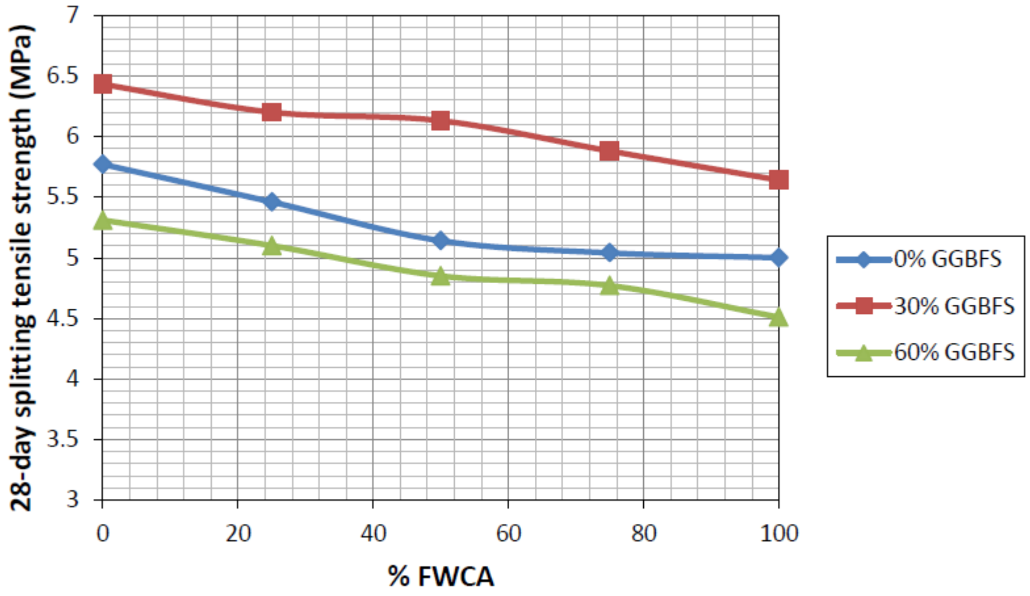


Figure 7: Indirect tensile strength of the high strength mortars at 28 days.

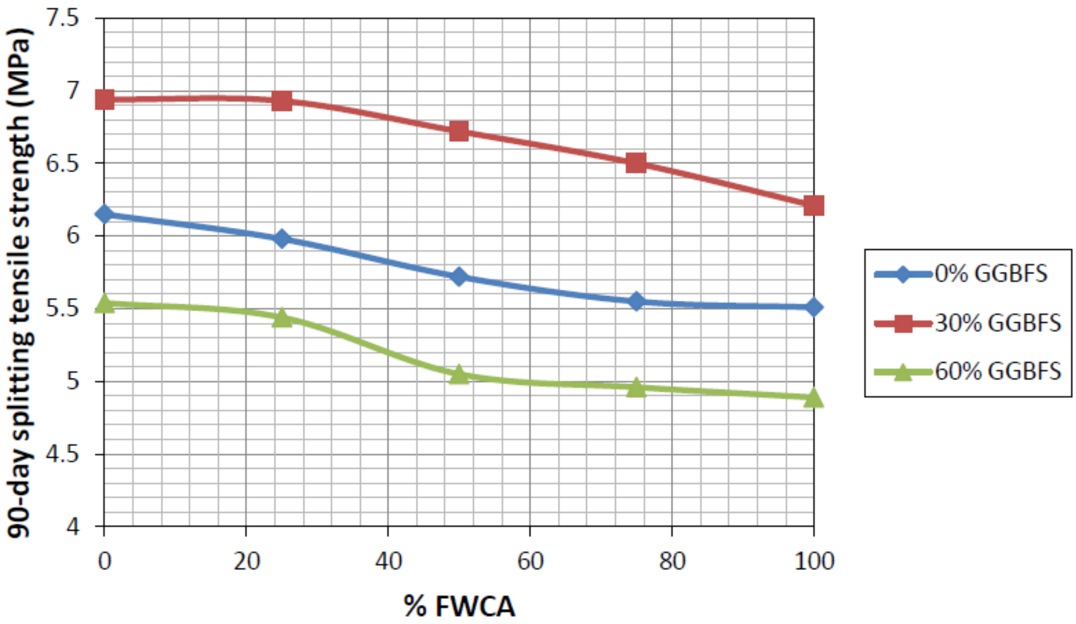


Figure 8: Indirect tensile strength of the high strength mortars at 90 days.

4.3. Net Flexural Strength

The net flexural strength results are graphically represented in Figure 9. In this figure, the effects of FWCA replacement level and GGBFS content are displayed. The net flexural strength was lower with higher FWCA content irrespective of GGBFS content. At 28 days, the partially and totally substitution of NFA by FWCA caused the net flexural strength to decrease by about 5-15% .As reported by (Andal *et.al.*, 2016), the drop in tensile strength is related to the less strength, less density, and larger porosity of waste concrete aggregates compared to natural aggregates.

The initial substitution of GGBFS (30%) increased the net flexural strength of mortar while the final substitution of GGBFS (60%) diminished it. The negative impact of FWCA on the flexural strength was reduced or even eliminated by the use of 30% GGBFS. For instance, the 28-day net flexural strength of mix N0R100G30 and mix N100R0G0 was 6.83 and 6.48 MPa, respectively (i.e., there was an improvement in the strength of about 5% though NFA was fully replaced by FWCA).

4.4. Fracture Energy and Toughness

The load-displacement plots shown in Figures 10-12 suggested that the reference mixes which were made with natural aggregates showed the greatest peak loads followed by mixes with 50% FWCA and then 100% FWCA. These findings were valid regardless of the GGBFS replacement level. At 30% GGBFS, for instance, the peak loads were 190.44, 173.97, and 170.65 N for mixes N100R0G30, N50R50G30, and N0R100G30, respectively. In addition, the 30% GGBFS mortar mixes exhibited the greatest peak loads while the 60% GGBFS mortars showed the lowest peak loads. At a given GGBFS level, the toughness and fracture energy were lower as the FWCA increased as seen in Table 4 and Figure 13. There was a reduction of 7-21% in fracture energy of mortars due to the inclusion of 50 and 100% of FWCA, respectively. The FWCA derived from waste concrete consists of both original sand and mortar adhered to it. So, the new mortars produced with FWCA contain two ITZ. The first one is located between the virgin sand and the previous mortar while the second one is between the new paste and the FWCA. The presence of these two ITZs created the regions of weakness in the microstructure of the new mortars thus declining the fracture energy of the composites.

Furthermore, the best toughness and fracture energy were recorded for mortar mixes with the GGBFS content of 30%, while the bad ones were observed for those with GGBFS content of 60%.

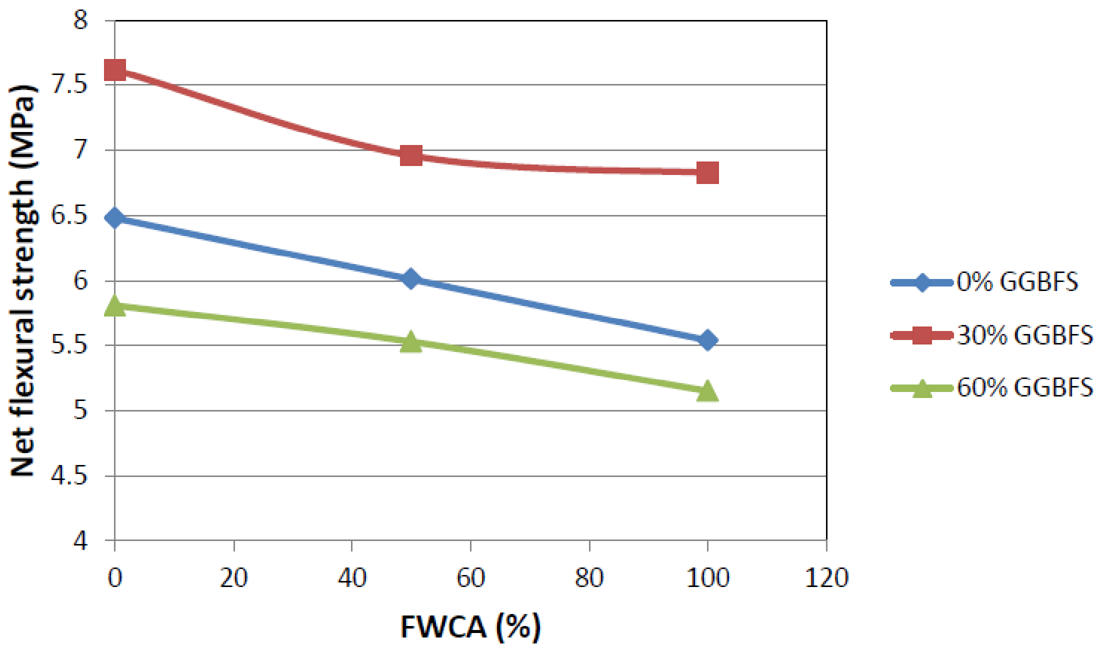


Figure 9: Influence of FWCA percentage on the 28-day net flexural strength for different GGBFS levels.

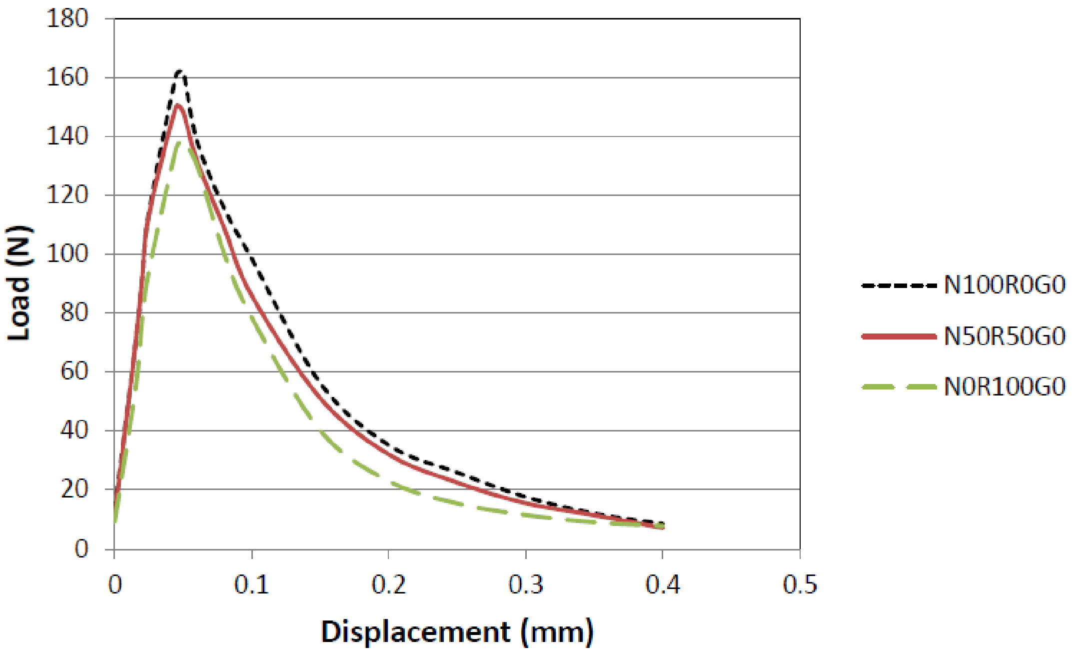


Figure 10: Load-displacement plots for high strength mortars with 0% GGBFS at 28 days.

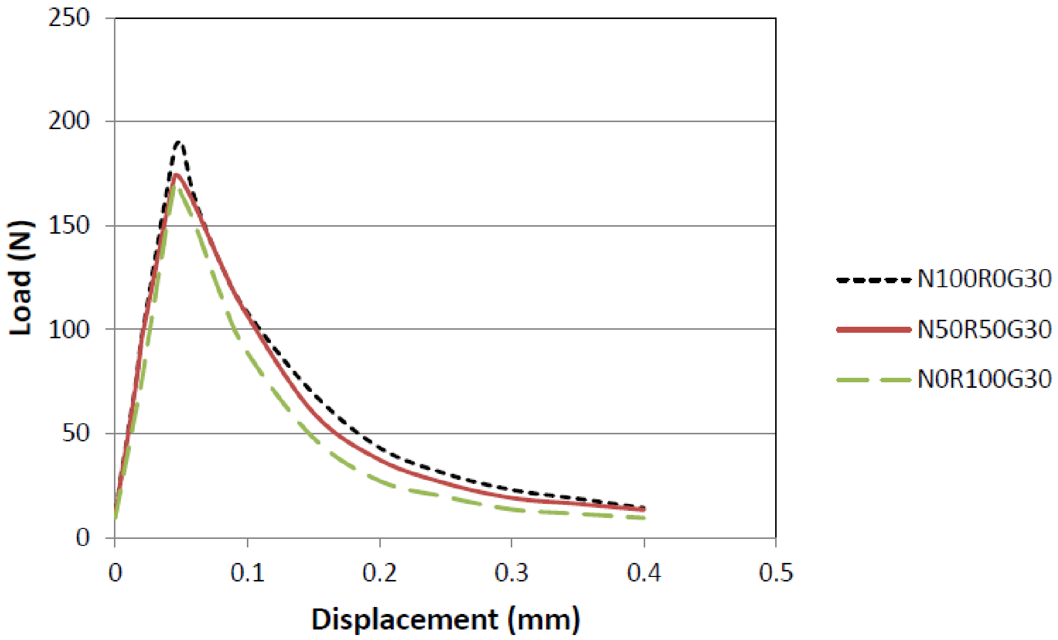


Figure 11: Load-displacement curves for high strength mortars with 30% GGBFS at 28 days.

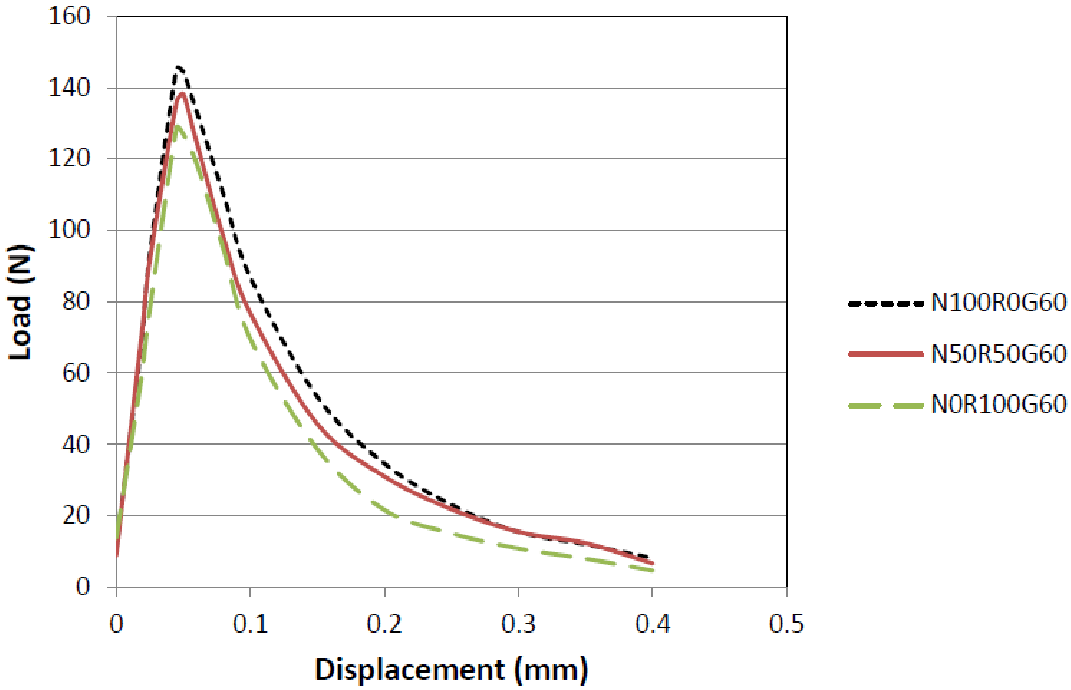


Figure 12: Load-displacement curves for high strength mortars with 60% GGBFS at 28 days.

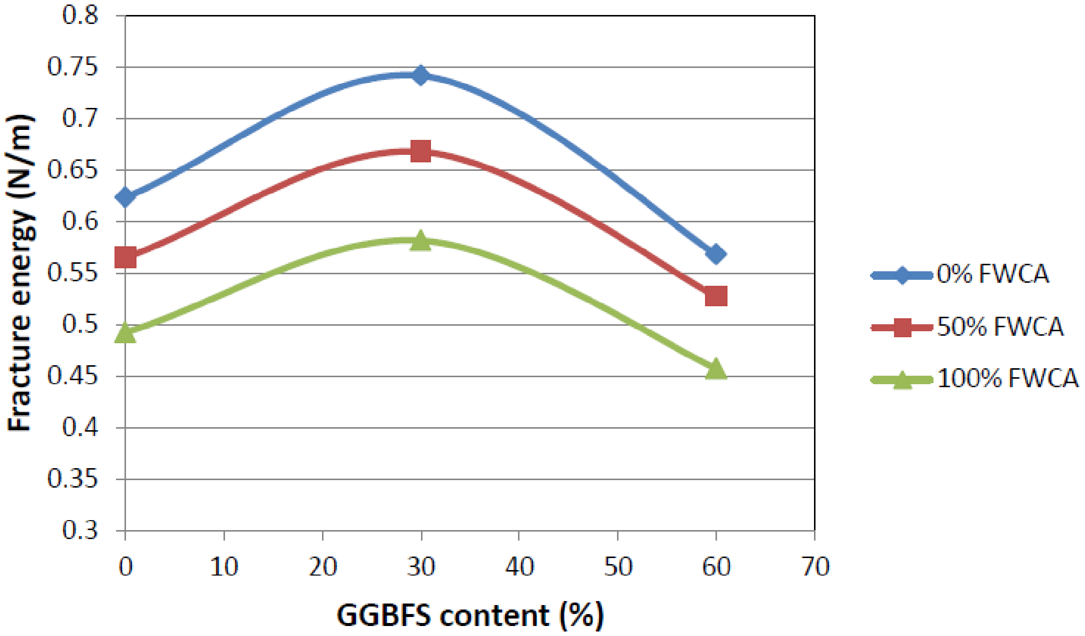


Figure 13: 28-day fracture energy for different high strength mortars.

5. The Variance Analysis (ANOVA)

The analysis of general linear model (GLM-ANOVA) was carried out on the compressive and splitting tensile strength test results at a level of significance of 0.05. This model is considered as a good tool to identify whether the experimental parameters affect the test results statistically. Moreover, the GLM-ANOVA model is used to determine the effectiveness of the interactions of the independent variables on the dependent variables. In the analysis, the total sum of squares, which consists of sum of squares (SS) of residual random error and SS of individual factors, is determined. The impact of separate factors is found by testing the hypothesis of the variance quality (Hicks, 1982).

The software, called MINITAB was adopted to analyze the data derived from the experiments of the present study. Two strength properties namely compressive and splitting tensile strengths were chosen as dependent variables while the FWCA percentage, GGBFS percentage, and age were selected as independent variables. Table 5 summarizes the statistical results. Value of p indicates whether the independent variable is statically significant on the test results such that the independent variable is effective when the value of p is lower than 0.05. From Table 5, it is obvious that the experimental parameters namely, FWCA percentage, GGBFS percentage, and age were statistically significant on the compressive and splitting tensile strength because the p-value in all cases was less than 0.05. However, the ANOVA analysis was also indicated that the age of curing had a best contribution to all investigated strength properties followed by GGBFS level and then FWCA percentage. For all the strength types, the contribution percent for age of curing was varied between 56.45% and 73.97%. The GGBFS and FWCA contributed to the strength by 16.88-29.08% and 2.3-7.05%, respectively. In other words, the FWCA percentage had the lowest impact on the strength properties among the investigated parameters.

Table 4: Fracture parameters of high strength mortars at 28 days.

Mix code	Net flexural strength (MPa)	Toughness (N.mm)	Fracture energy (N/m)
N100R0G0	6.48	22.468	0.62363
N50R50G0	6.01	20.301	0.56502
N0R100G0	5.54	17.59	0.49235
N100R0G30	7.62	26.891	0.74185
N50R50G30	6.96	24.171	0.66796
N0R100G30	6.83	20.949	0.58175
N100R0G60	5.81	20.399	0.56819
N50R50G60	5.53	18.914	0.52749
N0R100G60	5.15	16.293	0.45727

Table 5: ANOVA analysis of the experimental results.

Dependent variable (Response)	Independent variable (Experimental factor)	Degree of freedom (DF)	Sequential sum of squares (SS)	Value of F	Value of P	Significance	Contribution percentage
Compressive strength	FWCA content	4	213.3	3.03	0.030	Yes	2.30
	GGBFS content	2	1560.2	44.34	0.000	Yes	16.88
	Age	2	6838.8	194.36	0.000	Yes	73.97
	Error	36	633.3	-	-	-	6.85
Splitting tensile strength	FWCA content	4	2.757	8.55	0.000	Yes	7.05
	GGBFS content	2	11.372	70.55	0.000	Yes	29.08
	Age	2	22.075	136.94	0.000	Yes	56.45
	Error	36	2.902	-	-	-	7.42

6. Conclusions

1. The partial and full substitution of NFA by FWCA led to decline the compressive strength of high strength mortars and in general as the percentage of FWCA increased the compressive strength diminished. This finding was valid at all investigated ages and irrespective of whether the mortar mixes were made with GGBFS or without it. Nevertheless, the drop in compressive strength was below 15% in all cases.
2. It was found that both splitting tensile and net flexural strengths of high strength mortars were also lower with increasing FWCA content regardless of age and GGBFS replacement level.
3. The early age (7-day) strength of all mixes decreased due to the substitution of 30% or 60% OPC by GGBFS because of the slow rate of hydration of this type of supplementary cementitious material. At later ages, namely 28 and 90 days, all strength types improved because of the inclusion of 30% of GGBFS, while they were diminished by the incorporation of 60% GGBFS. In other words, a 30% GGBFS was optimum for the best strengths of mortars.
4. The replacement of 30% of OPC by GGBFS counterbalanced the strength reduction caused by the full or partial replacement of NFA by FWCA such that the strength of mortars made with FWCA and 30% GGBFS was comparable to or even exceeded that of mortars produced with only NFA.
5. Comparing the 0% GGBFS mixes made with 100% NFA and the 30% GGBFS mixes made with 100% FWCA suggested that the fracture energy and toughness of both types of mixes were almost comparable.
6. In conclusion, the results of the current experimental study suggest that the high strength mortars could be produced with FWCA especially when the 30% of OPC is replaced by GGBFS which is a by-product material. This will not only reduce the environmental damage caused by waste materials like waste concrete and GGBFS but also decrease the cost of production of cement-based materials.

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