INTERNATIONAL JOURNAL OF SUSTAINABLE CONSTRUCTION ENGINEERING AND TECHNOLOGY
Vol. 13 No. 3 (2022) 159-173

IJSCET

http://penerbit.uthm.edu.my/ojs/index.php/ijscet
ISSN : 2180-3242 e-ISSN : 2600-7959

International Journal of Sustainable Construction Engineering and Technology

The Influence of Hybrid Fibers and Nanomaterials (Nano Glass with Nano Slag) on the Behavior of Reactive Powder Concrete

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DOI: https://doi.org/10.30880/ijscet.2022.13.03.015
Received 1 March 2022; Accepted 13 March 2022; Available online 10 December 2022

Abstract: The new production of Reactive Powder Concrete (RPC) has become an interesting topic due to the dramatic properties that such materials can give. Thus, this study has been prepared to observe the properties of RPC mixes reinforced with micro steel fibers (MSF) by the order of 2% volumetric fractions (vol.). As well, hybrid fibers from MSF, sisal fiber (SIF), and also human hair fibers (HHF) have been included in the RPC mix in the order of 1.5% MSF plus 0.5% SIF, 1.5% MSF plus 0.5% HHF, and 1.5% MSF plus 0.25% SIF plus 0.25% HHF, respectively. Besides, the inclusion of two different nanomaterials combination by 2.5% Nano glass powder (NG) and 2.5% Nano Iron slag powder (NS) was performed into that reinforced RPC. The preparation of these different RPC mixes was followed by testing them to investigate the performance of such RPC based on the properties of flowability, compressive strength, tensile strength, flexural strength, flexural toughness, and static modulus of elasticity. The results showed that the incorporation of 2%MSF increases the compressive strength, tensile strength, and flexural strength by 6.76%, 12.45%, and 14.34%, respectively, at 90 days. Whereas, the reinforcing of RPC by 1.5% micro steel fibers (MSF) with 0.25% sisal fibers (SIF) and 0.25% human hair fibers (HHF) rises the values of compressive strength, tensile strength, and flexural strength by 5.38%, 11.59%, and 14.05%, respectively, at age of 90 days. Moreover, the uses of nanoparticles as 2.5%NG with 2.5%NS in addition to 2%MSF increase the compressive strength, tensile strength, and flexural strength by 33.09%, 36.05%, and 43.68% at age of 90 days, respectively. The use of 1.5% MSF plus 0.25% SIF plus 0.25% HHF with the mentioned nanoparticles (2.5%NG and 2.5% NS) boosts the best performance by converting such concrete from brittle material to ductile material.

Keywords: Nano slag powder, nano glass powder, human hair fibers, hybrid fibers, RPC

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1. Introduction

Reactive Powder Concrete (RPC) considers a new type of concrete successfully developed by Richard towards the end of the twentieth century [1]. This type of concrete represents one of the most recent technological leaps witnessed by the construction industry due to its characterizations of ultra-high performance [2]. It consists of very fine powders such as cement and silica fume, fine sand, very low water content, and a high dosage of superplasticizer in addition to fibers [3]. Although it is not contained coarse aggregate, it is considered one of the best types of concrete due to its ultra-high performance and superior properties [4].

As compared to ordinary cement-based composites, RPC can contribute to reducing the amount of reinforcing steel bars, and the weight of the structure. It also increases the service life of the structure [5]. The primary improvements of RPC include particle size homogeneity, porosity, and microstructure [1]. The elimination of the coarse aggregate, reduction water to binder ratio, reduction of the calcium oxide to silicon dioxide ratio by using the silica elements, and incorporation of steel fibers into the RPC matrix give such concrete unique properties [6]. The compressive strength, flexural strength, and elastic modulus of this type of concrete can reach more than 200 MPa, 40 MPa, and 60 GPa, respectively, with excellent durability [5].

The use of very fine sand instead of ordinary aggregate in RPC mixes requires a high amount of cement ranging from 900-1000 kg/m3[2]. So, cement material is the main component of reactive powder concrete and it is responsible for the ultra-high strength of the such type of concrete, especially the compressive strength. The major compounds of cement responsible for providing concrete strength are Alite (3CaO.SiO2) and Belite (2CaO.SiO2) [7]. During hydration of cement, Alite and Belite react with water and form calcium silicate hydrate gel (3CaO.2SiO2.3H2O) and calcium hydroxide (Ca(OH)2). The calcium silicate hydrate gel forms the binder material of the particles in the cementitious matrix [8]. On the other hand, the use of a high amount of cement increases the production cost of concrete and the heat of hydration, which leads to potential hazards related to shrinkage and creep problems [9]. Also, the accumulation of solid waste materials resulting from industrial processes like iron slag and silica fume in addition to those resulting from daily use like broken glass have negative effects on the environment. In order to decrease this environmental impact, saving in cement, and producing sustainable building material; glass powder, slag powder, and silica fume were considered in this study. These materials were used as a partial substitute for cement to produce sustainable RPC.

Moreover, the inclusion of the fibers, especially steel fibers in the RPC leads to enhancing the post-cracking tensile strength and thus they improve the ductility of the material [10]. Such fibers can be hybrid with other types of fibers in reinforcing concrete [11-12]. Many researchers have reported the possible use of natural fibers in cementitious matrices [13-14]. Sisal fibers and human hair fibers are some types of natural fibers that have been used in reinforcing concrete. Many previous studies have exhibited the treatment of sisal fibers before using them in cement-based composites. The chemical treatment of sisal fibers has a positive impact on its durability. The use of chemical solutions like acetic acid, sodium hydroxide, and acetic anhydride with low concentrations improves the strength and durability of these fibers [15]. On the other hand, the inclusion of human hair fibers with mono form or hybrid form into the cementitious matrix has interested many researchers in the twentieth century [16-17]. The use of such fibers contributes to decreasing the accumulative waste materials in the environment. Moreover, these fibers improve the physical and mechanical properties of concrete [18-20]. Continuously, human hair fibers lead the cementitious matrix to be more durable.

Thus, the objectives of this study are to investigate the different properties of; 1) RPC which is reinforced with mono and hybrid fibers only, 2) Reinforced RPC which is included Nano-powders (Nano glass and Nano slag). The flowability, compressive strength, tensile strength, flexural strength, flexural toughness, and static modulus of elasticity were considered in this study.

2. Experimental Study

2.1 Materials

Ordinary Portland Cement (OPC) with the commercial name Delta cement was used in this study. Supplementary cementitious materials which are silica fume, iron slag, and glass powder were used in this research. The silica fume (SF) was brought from MSASA-Construction Solutions for Africa. The iron slag powder (ISP) was obtained from the iron production factory in Mosul, Iraq. The glass powder (GP) was obtained from a glass recycling plant in Mosul- Iraq. The properties for each of OPC, SF, ISP, and GP are with accordance to ASTM C150 [21], ASTM C1240 [22], ASTM C989 [23], and ASTM C618 [24], respectively. The physical properties and the chemical composition of such materials are shown in Tables (1a -1b). Local river sand with a maximum aggregate size of 0.6 mm was used in the study.

The work has also required the use of a superplasticizer. The properties of this admixture (innovative polycarboxylic ether superplasticizer (SP.)) was shown in Table 2. Whereas, the different two types of local nanomaterials have been used in this work; Nano glass powder (NG) as well as, Nano iron slag powder. Figures 1 and 2 illustrate the SEM images for both materials.

The micro steel fibers (MSF) have been procured from Maqiao-China at Jiangsu Bositai steel Fiber Co., Ltd. The treated sisal fibers (SIF) have been procured from the local markets in Mosul-Iraq. Human hair fibers (HHF) have been collected from local hair salons in Mosul-Iraq. They were in balling form as waste material and they have been used after washing and air-drying. The fibers' properties are shown in Table 3.

2.2 Mix Proportions and Testing

The preparation of RPC mixes requires the use of sand amount less than that of conventional concrete [1]. Thus, the amount of cement in such mixes is high. In order to produce sustainable RPC, the mixes have been prepared by using GP, ISP, and SF as partial replacements of OPC. The replacement percentages of OPC by GP, ISP, and SF were 8%, 12%, and 10%, respectively. These percentages were selected depending on a previous study [25]. Moreover, the amount of fine sand used in this study was closed to that of binder material(OPC+GP+ISP+SF) to give superior properties of RPC [26-28]. Consequently, the binder mix proportion (OPC+ GP+ISP+SF) to sand was 1:1. The water(W) + chemical admixture(A) / binder(B) ratio was 0.28. The dosage of superplasticizer was 1% by weight of binder materials, while the dosage of de-foamer(De) was 0.3% by weight of superplasticizer. The total number of RPC mixes prepared in this study was nine. The first one was M1 which is a control mix. The next RPC mix was MS. Such mix differentiates from M1 due to the incorporation of 2% MSF. The mixes MH1, MH2 and MH3 have been prepared using 1.5%MSF+0.5%SIF, 1.5%MSF+0.5% HHF, and 1.5%MSF+0.25% SIF+0.25% HHF, respectively. The mixes MNS, MNH1, MNH2, and MNH3 have been prepared by 2% MSF with 2.5%NG+2.5% NS, 1.5%MSF+0.5%SIF with 2.5%NG+2.5%NS, 1.5%MSF+0.5%HHF with 2.5%NG+2.5%NS and 1.5%MSF+0.25%SIF+0.25%HHF with 2.5%NG+2.5% NS, respectively. The details of all these mixes are shown in Table 4.

The flow test was performed for all RPC mixes according to ASTM C1437 [29]. A mini-slump cone, a mini tamping rod, and a flow table were used to conduct this test, as shown in Fig. 3. The average flow diameter for each of the RPC mixes was recorded, as shown in Table 5.

Three samples (50×50×50 mm) for each RPC mix were prepared and tested as per ASTM C 109 [30] as exhibited in Fig. 4a. Briquette molds were used in preparing the specimens according to CRD-C260-01[31] for testing the direct tensile strength as shown in Fig. 5.

The flexural strength of RPC specimens was conducted according to ASTM C348[32], while the flexural toughness value was determined as per ASTM C1609 [33] as exhibited in Fig. 6.

The cylindrical RPC specimens of size φ 100mm × 200mm were used to measure static elastic modulus value as shown in Fig 4b according to ASTM C469[34].

3. The Results and Discussion for Reactive Powder Concrete Samples

RPC specimens were subjected to six tests to determine their properties. The tests were flowability, compressive strength, direct tensile strength, flexural strength, flexural toughness, and, modulus of elasticity. The obtained results from the experimental work with discussion for each test were shown below:

3.1 Flow Ability

The test results for all fresh RPC mixes are tabulated in Table 5. For RPC mixes reinforced with only fibers (MS, MH1, MH2, and MH3), the flowability values were decreased with the addition of the fibers. The incorporation of micro steel fibers (MSF) with 2% led to a decrease in the flowability of RPC mixes by 3.04%. This might be due to increased specific surface area associated with the increase of fiber content [35]. Besides, the random distribution of steel fibers may affect the fluidity of fresh RPC [28, 35-36].

On the other hand, the hybrid fibers (micro steel fibers (MSF) and sisal fibers (SIF) or/and human hair fibers (HHF)) also affected the flowability of the RPC mix. The inclusion of 1.5% MSF + 0.5% SIF, 1.5% MSF + 0.5% HHF, and 1.5% MSF + 0.25% SIF + 0.25% HHF decreased the fluidity by 3.48%, 2.17% and 2.61%, respectively, in comparison with plain RPC (M0). This can be attributed to the combined effect of the fibers used (micro steel fibers with sisal fibers and/or Human hair fibers). The reduction in flowability values of mixes reinforced with hybrid fibers (MH1, MH2, and MH3) was closed or less than that of the mix reinforced with 2%MSF(MS). Although the chemical composition for both the untreated sisal fibers and human hair make them water absorbent [37-38], the treatment of such fibers before using them was contributed to decreasing the water absorption of RPC mixes.

For RPC mixes reinforced with fibers and nanomaterials (MNS, MNH1, MNH2, and MNH3), The flowability values were also decreased in comparison with plain RPC mix(M0). The reduction in flowability value of MNS, MNH1, MNH2, and MNH3 was about 4.35%, 4.35%, 3.48%, and 3.91% respectively. This can be ascribed to the use of both fibers and nanomaterials (Nano glass and Nano slag) in these mixes.

3.2 Compressive Strength

Table 6 shows the results obtained from the compression test for RPC mixes. The results indicate that the inclusion of 2% MSF into plain RPC can slightly contribute to enhancing the compressive strength. Thus, the increase rates were by 5.88%, 6.65 %, and 6.76 % at 7, 28, and 90 days, respectively, in comparison with plain RPC (M0).

The increase in the compressive strength of cementitious matrix using steel fibers has been observed by many researchers [39-40]. The development of the strength can be ascribed to the good bond strength between cementitious matrix and steel fibers [28, 41]. In addition, the incorporation of steel fibers into cementitious matrix can delay the formation of micro-cracks and arrest their propagation afterward up to a certain extent of the fibers' volume fraction

[40,42]. Moreover, the results of compressive strength for RPC specimens reinforced with 2% micro steel fibers (MSF) in mono form and 1.5% MSF in hybrid form showed a small difference. At age of 7 days, the compressive strength of RPC containing 1.5%MSF+0.5%SIF, 1.5%MSF+0.5%HHF, and 1.5%MSF+0.25%SIF+ 0.25%HHF increased by 4.87%, 4.30%, and 5.25% respectively. At age of 28 days, the compressive strength increase was by 4.37%, 4.08%, and 5.50%, respectively. At age of 90 days, the compressive strength increase was by 5.19%, 4.99%, and 5.38%, respectively. The reason may be attributed to the identical percent of SIF or/and HHF which did not lead to cause balling and lumping of fibers during the mixing process as well as high elastic modulus, the high tensile strength of these fibers, and their ability to reduce the micro-fractures or cracks of hardened concrete specimens [43-44].

The compressive strength of RPC, reinforced with different types of fibers and supported by nano materials, was obviously improved in comparison with plain RPC. The relative increase rates of MNS, MNH1, MNH2 and MNH3 were 21.12%, 15.86%, 13.31% and 19.63% at age of 7 days, 32.87%, 27.12%, 23.08% and 29.14% at age of 28 days, and 33.09%, 27.56%, 25.17% and 30.86% at age of 90 days, respectively. The incorporation of the identical amount of fibers in mono form and hybrid form in addition to the optimum amount of Nano glass (NG) and Nano slag (NS), in combination form, into the RPC mixture might be responsible for the remarkable enhancement of compressive strength for four mixes mentioned above.

3.3 Tensile Strength

The results of tensile strength for RPC mixes are shown in Table 7. It was observed that the incorporation of micro steel fibers with 2% by the total volume of concrete leads to increasing the tensile strength by 15.59% and 12.45% at age of 28 and 90 days, respectively, compared with plain RPC (M0). The improvement in the tensile strength can be attributed to using micro steel fibers with acceptable dosage. Thus, the inclusion of these fibers into the cementitious matrix was enabled it to sustain the structural integrity towards tensile load after first cracking by bridging cracks and transferring the load across the cracks [45]. The development of cement-based composites under tension stress using steel fibers has been observed by many researchers [46-47].

In hybridization case, the tensile strengths of MH1(1.5%MSF+0.5%SIF), MH2(1.5%MSF+0.5% HHF) and MH3(1.5%MSF+0.25%SIF+0.25%HHF) were also enhanced by 13.98%, 13.44% and 15.32% at age of 28 days and by 10.94%, 10.52% and 11.59% at age of 90 days, respectively, in comparison with M0(plain RPC).

The inclusion of 2%MSF, 1.5%MSF+0.5%SIF, 1.5%MSF+0.5%HHF, and 1.5% MSF+0.25% SIF+ 0.25%HHF in addition to 2.5% NG and 2.5%NS developed the tensile strength by 39.78 %, 31.18%, 26.61% and 34.95% at age of 28 days and by 36.05%, 25.32%, 20.17%, and 26.82% at age of 90 days, respectively, compared to plain RPC(M0). The increase in the compressive strength of RPC specimens has been obtained due to the use of nanoparticles and fibers, which also leads to a tensile strength increase. The development of tensile strength of cementitious matrix by incorporation of nanoparticles has been noticed by several researchers [48-49].

3.4 Flexural Strength

Table 8 lists the test results of RPC specimens. As illustrated in the mentioned Table, the inclusion of fibers, into RPC mixes, has a significant role in the improvement of modulus of rupture. RPC reinforced with 2% MSF has observed a significant development in the flexural strength compared with plain RPC (M0). The increasing rates were 21.89% at age of 7 days, 19.36% at age of 28 days, and 14.34% at age of 90, respectively. This is due to the ability of fibers to convert the concrete from brittle material to ductile material as well as the use of the acceptable level of such fibers and the homogeneous distribution of it into the RPC matrix. The improvement in flexural strength of RPC utilizing steel fibers has also been noticed by many researchers [50-51].

In hybridization case, the flexural strength of RPC reinforced with 1.5%MSF+0.5%SIF (MH1), 1.5%MSF+0.5%HHF (MH2), and 1.5%MSF+0.25%SIF+0.25%HHF (MH3) was also increased by 20.23%, 16.91% and 20.74% respectively at age of 7 days and by 17.71 %, 15.41% and 17.96% respectively at age of 28 days and by 13.58%, 11.76% and 14.05% respectively at age of 90 days in comparison with plain RPC (M0). As shown in Table 8, the inclusion of hybrid fibers also led to increasing the strength, at different ages. This can be attributed to the ability of SIF and HHF to enhance the mechanical properties of concrete. The incorporation of SIF into concrete can be contributed to providing the same level of flexural strength as synthetic fibers such as polypropylene fibers as well as gaining ductility and flexural toughness to cement-based composite [52]. Besides, the inclusion of human hair fibers can contribute to enhancing the flexural strength of concrete slightly and decrease its production cost [20,53]. On the other hand, the incorporation of 2%MSF into RPC gave an increased rate in the flexural strength higher than that of containing1.5%MSF+0.5%SIF, 1.5%MSF+0.5%HHF, or 1.5%MSF+0.25%SIF+0.25%HHF. This can be attributed to the high elastic modulus in addition to the high tensile strength and flexural rigidity of micro steel fibers in comparison with those of natural fibers (sisal fibers and human hair fibers).

In general, RPC specimens reinforced with the fibers and nanoparticles were noticed a high increasing rate in flexural strength in comparison with plain RPC. The specimens reinforced with 2% MSF and 2.5%NG+2.5%NS have reached the optimum flexural strength which is equal to 24.44 MPa. Moreover, the flexural strength of specimens reinforced with hybrid fibers and nanoparticles exhibited a small difference from that reinforced with mono fibers (2%MSF) and nanoparticles. The flexural strength increase can be ascribed to the inclusion of the optimum amount of nanoparticles

(2.5%NG+2.5%NS) and fibers into RPC. This leads to generating an additional amount of C-S-H gel and C-F-H gel (resulted by chemical reaction of NG and NS with Ca(OH)2), as well as, the filling ability of nanoparticles to densify the cementitious matrix and delay the formation of micro-cracks [49,54-55]. Thus, the use of such materials obviously improved the flexural strength.

3.5 Flexural Toughness

The flexural toughness results of RPC reinforced with nanoparticles(25%NG+2.5%NS) and different percentages of fibers at age of 90 days, were shown in this section. The standard specification for computing flexural toughness of reinforced cementitious matrix ASTM C1609[33] has been depended on to calculate flexural toughness parameters of RPC specimens prepared in this study. Toughness is generally defined as energy absorption capacity [56]. The area under the load-deflection curve for bending can be used as an index to evaluate the energy-absorbing capacity or toughness of the material. Increased toughness also means improved performance in resisting fatigue, impact, and impulse loading. Moreover, the improved toughness also leads to better ductility [56]. Values of toughness indices, residual strength factors, and first-crack strength may be used for comparing the performance of various nanoparticles and fiber-reinforced concretes during the mixture proportioning process. Table 9 lists flexural performance parameters PL, PD, P600, P150, F600, F150, T600, and T150 for RPC, included nanoparticles (2.5%NG+2.5%NS) and different types of fibers, according to ASTM C 1609[33]. The results indicated that the flexural toughness improves with the incorporation of nanomaterials and fibers. It can be seen, in Table 9, that the fiber fractions of 2%MSF, 1.5%MSF+0.5SIF, 1.5%MSF+0.5%HHF, or 1.5% MSF+0.25%SIF+0.25%HHF have a clear effect on the toughness parameters. This can be attributed to the ability of the fibers to arrest cracks at both the micro and macro levels. At the micro-level, the fibers inhibit the initiation of cracks, whereas, at the macro level, the fibers provide effective bridging and impart sources of toughness and ductility [42].

The highest increment of T150 was observed at the incorporation of 2%MSF or 1.5%MSF+0.25% SIF+0.25%HHF in RPC. For RPC specimens reinforced with 2%MSF, the T150 was 3.99. Besides, T150 of RPC reinforced with hybrid fibers (1.5%MSF+0.25%SIF+0.25%HHF) was 3.71. The obvious increment in the parameters of toughness for MNS(2%MSF) and MNH3(1.5%MSF+0.25%SIF+ 0.25%HHF) can be ascribed to stiffness property and high performance of MSF in mono and hybrid form which make them more efficient in this stage. Fig. 8. displays the combined effect of hybrid nanoparticles and fibers on the flexural toughness, due to the relationship between load and deflection of RPC reinforced with such materials.

3.6 Static Modulus of Elasticity

Static elastic modulus test was performed on cylindrical specimens of dimensions φ100mm×200mm. At age 90 days the modulus of elasticity of RPC specimens was measured as per ASTM C469 [34]. The experimental results, presented in Table 10, indicate that the static elastic modulus value of RPC improves with the addition of the fibers and nanoparticles into it. RPC specimens reinforced with mono and hybrid fibers (MSF, SIF, and/or HHF) and contained nanoparticles (NG and NS) were noticed an increase in the modulus of elasticity. The increase rates were ranged from 7.79% to 15.55% in comparison with plain RPC specimens. The highest increment was found at MNS and the lowest increase was observed at MNH2. The variation of the modulus of elasticity for MNS, MNH1, MNH2, and MNH3 can be attributed to the type and quantity of fibers used in the mix. Besides, the behavior of such property was found to agree with the results of compressive strength for such mixes. This can be attributed to the similar effect of fibers on the properties of compressive and modulus of elasticity for RPC mixes [57].

4. Conclusions

Some conclusions can be revealed:

1. The incorporations of mono and hybrid fibers in RPC mixes have a positive effect on the mechanical properties of such concrete. The incorporation of 2% micro steel fibers volume fractions (MSF) increases the compressive strength, tensile strength, and flexural strength by 6.65%, 15.59%, and 19.36%, respectively, at 28 days and 6.76%, 12.45%, and 14.34%, respectively, at 90 days.
2. Reinforcing RPC by 1.5% micro steel fibers (MSF) with 0.25% sisal fibers (SIF) and 0.25% human hair fibers (HHF) rises the values of compressive strength, tensile strength, and flexural strength by 5.50%, 15.32% and17.96%, respectively, at age 28 days and by 5.38%, 11.59%, and 14.05%, respectively, at age 90 days.
3. The fluidity of RPC mixes decreases as the fibers content increases in the mixes. The use of mono fibers (2%MSF) and hybrid fibers (1.5%MSF+0.25%SIF+0.25HHF) decrease the flowability by 3.04% and 2.61%, respectively.
4. The inclusions of fibers with nanoparticles in RPC increase the strength of such concrete. The uses of 2.5%NG with 2.5%NS in addition to 2%MSF increase the compressive strength, tensile strength, and flexural strength by 32.87%, 39.78%, and 45.16%, respectively, at age of 28 days and by 33.09%, 36.05%, and 43.68% at age of 90 days.
5. The flexural toughness performance of RPC is improved with the inclusion of hybrid nanoparticles (2.5%NG+2.5%NS) and hybrid fibers. The use of 1.5% MSF + 0.25% SIF + 0.25% HHF with the mentioned nanoparticles

boosts the best performance by converting such concrete from brittle material to ductile material. In addition, the static elastic modulus is increased by 15.55% at age 90 days using 2%MSF with 2.5%NG and 2.5%NS.

Acknowledgment

The work described in this paper has been conducted in the laboratory of the technical engineering college of Mosul. This research represents part of the Master's thesis work of the second author.

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Table 1a - Physical properties of the OPC, SF, ISP and GP

Physical properties	OPC	SF	ISP	GP
Specific gravity, g/cm^3	3.15	2.1	3.2	2.32
Blaine's fineness, cm^2/g	3560	226000	8028	4094
Initial setting time, minute	117	-	-	-
Final setting time, hour	2:40	-	-	-

Table 1b - Chemical composition of the OPC, SF, ISP and GP

Chemical composition, %	OPC	SF	ISP	GP
Ferric oxide, Fe_2O_3	3.44	0.8	95.43	1.17
Calcium oxide, CaO	61.46	1.44	0.65	11.94
Silicon dioxide, SiO_2	19.53	93.29	4.03	72.71
Sulfur Tri oxide, SO_3	2.25	0.85	0.84	0.32
Alkalies ($K_2O + Na_2O$)	0.58	0.88	1.08	8.91
Manganese oxide, MnO	-	0.04	0.50	0.02
Magnesium oxide, MgO	3.82	0.14	0.14	1.48
Aluminum oxide, Al_2O_3	4.92	0.26	0.52	1.49
Loss of ignition (LOI)	3.11	-	-	-
C_3S	57.39	-	-	-
C_2S	13.53	-	-	-
C_3A	7.20	-	-	-
C_4AF	10.46	-	-	-

Table 2 - Technical description of chemical admixture*

Property or Feature	Superplasticizer	De-Foamer
Appearance	Yellowish liquid	Yellowish liquid
Density, g/cm^3	1.110±0.02	-
Chemical nature	-	Mixture with glycols and emulsifiers
PH	6.0±1	-
Solid content,%	50±2	-
Chloride content,%	Less than 0.10	
Ionic character	-	Nonionic

*The superplasticizer and de-foamer were produced by Marla-Chemicals company, Istanbul, Turkey

Table 3 - Properties of fibers used in this study

Property	MSF	SIF	HHF
Average fiber diameter, mm	0.225	0.225	0.2
Average fiber length, mm	13	18±2	18±2
Aspect ratio	58	80	90
Specific gravity, g/cm^3	7.82	1.4	0.4
Tensile strength, MPa	>2850	400-700	150-270

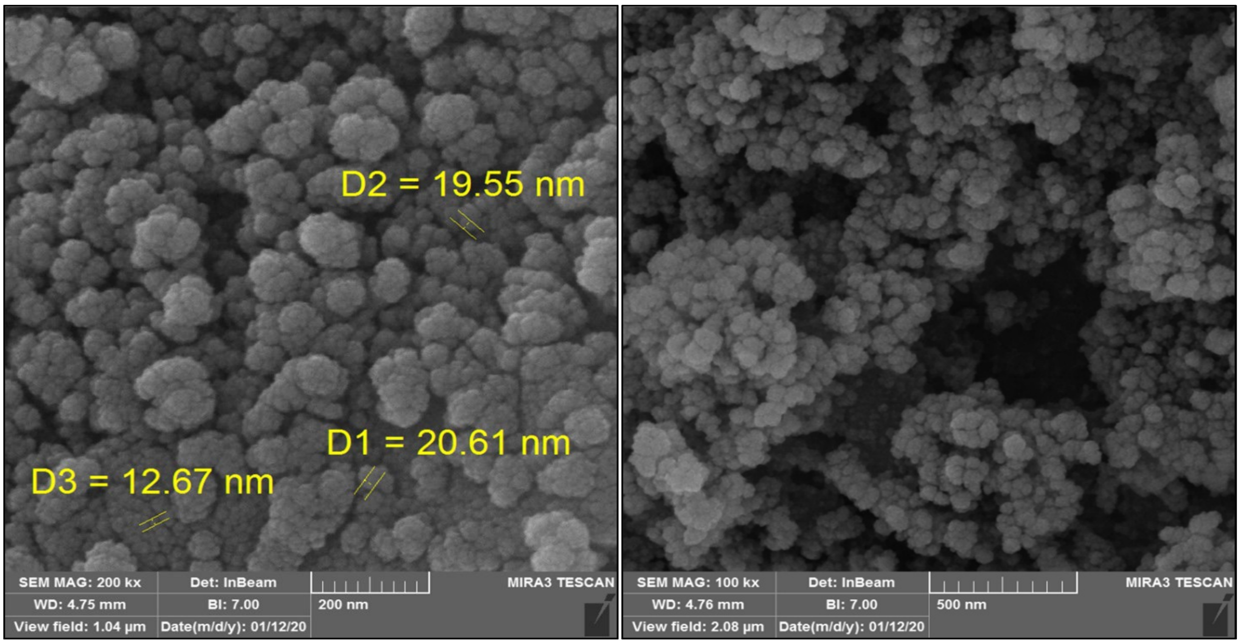

Fig. 1 - SEM images for Nano glass powder

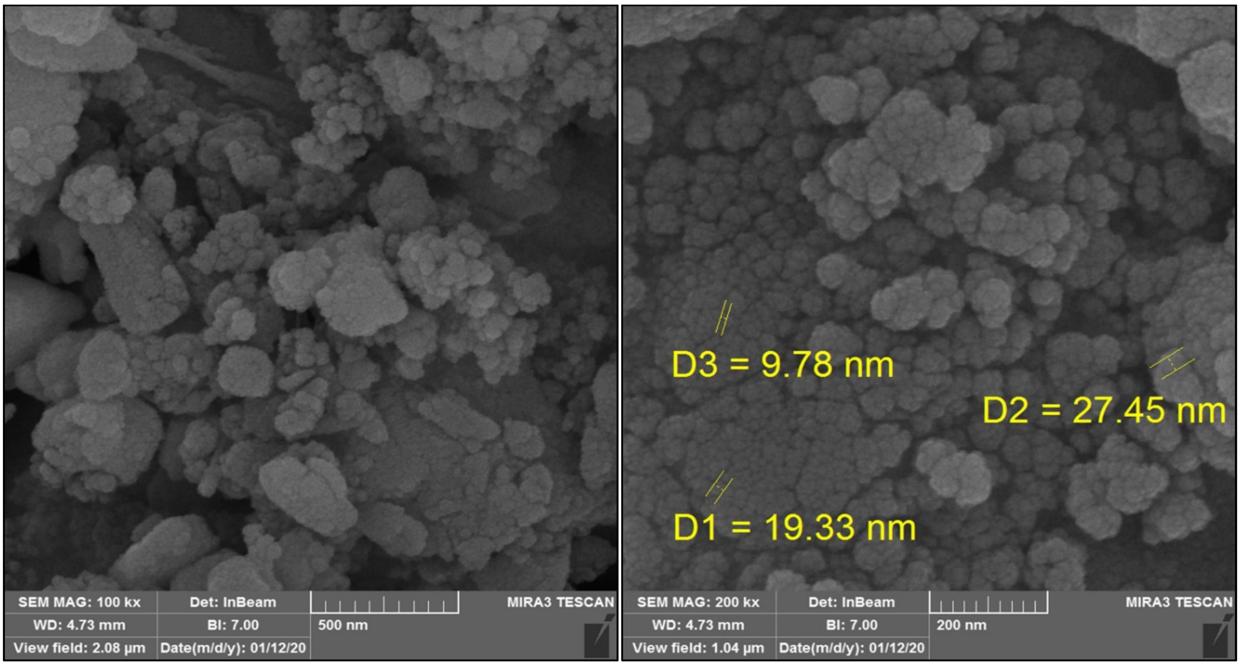

Fig. 2 - SEM images for Nano iron slag powder

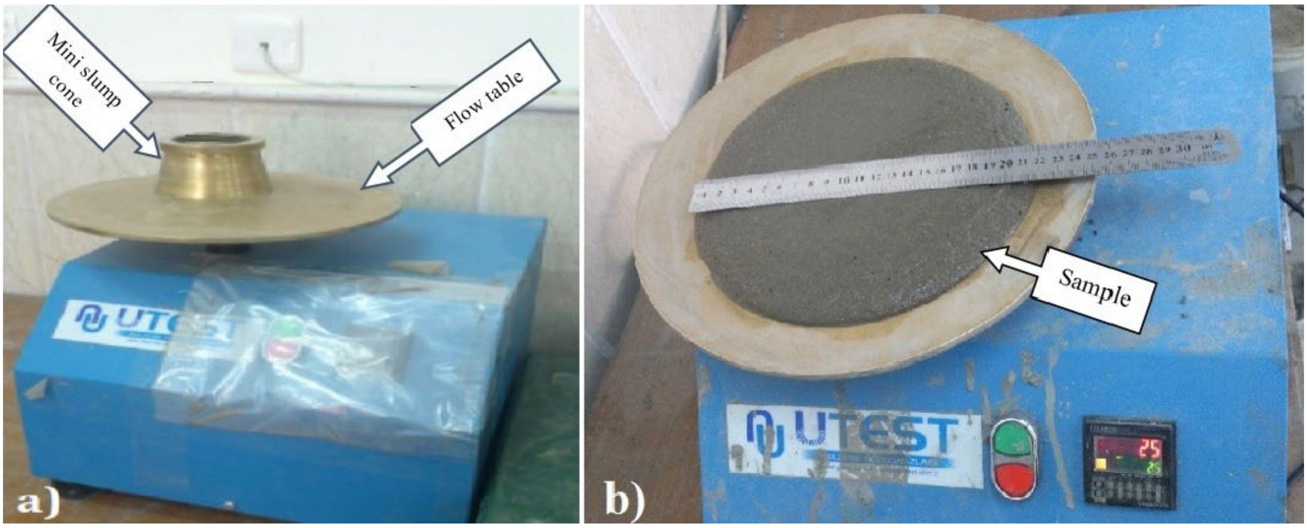

Fig. 3 - (a) Flow table and accessory apparatus; (b) The flow diameter measuring

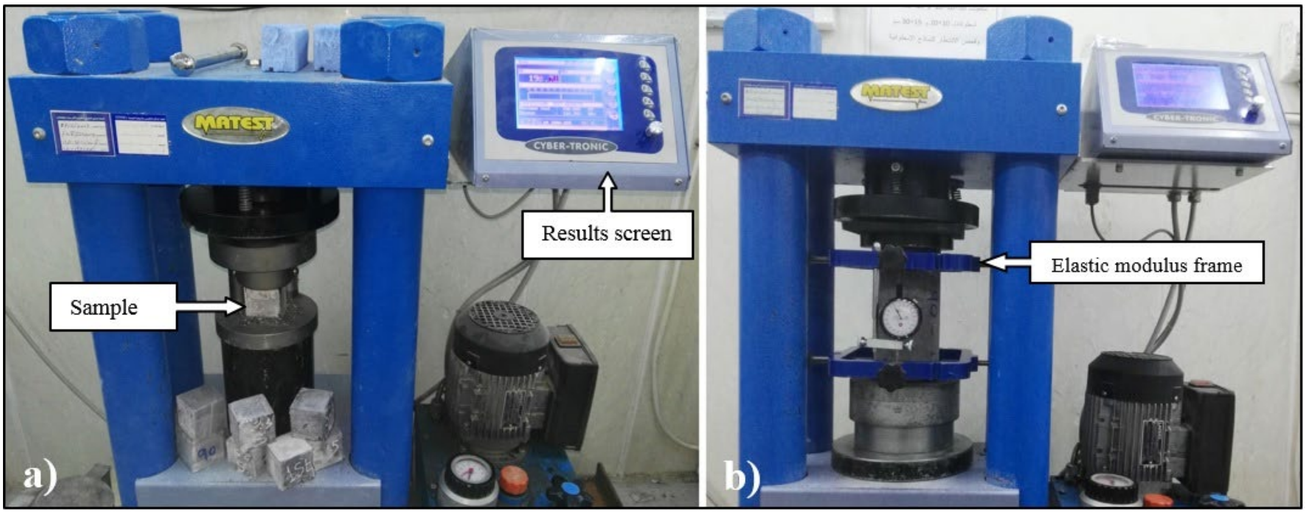

Fig. 4 - (a) Compression test; (b) Static elastic modulus test

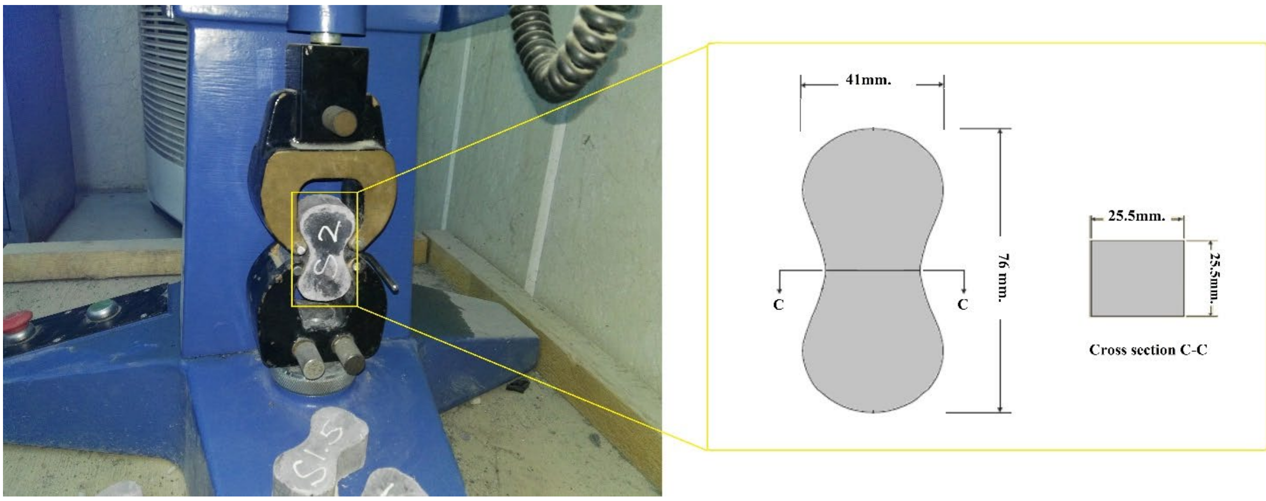

Fig. 5 - Tensile strength test for RPC specimens

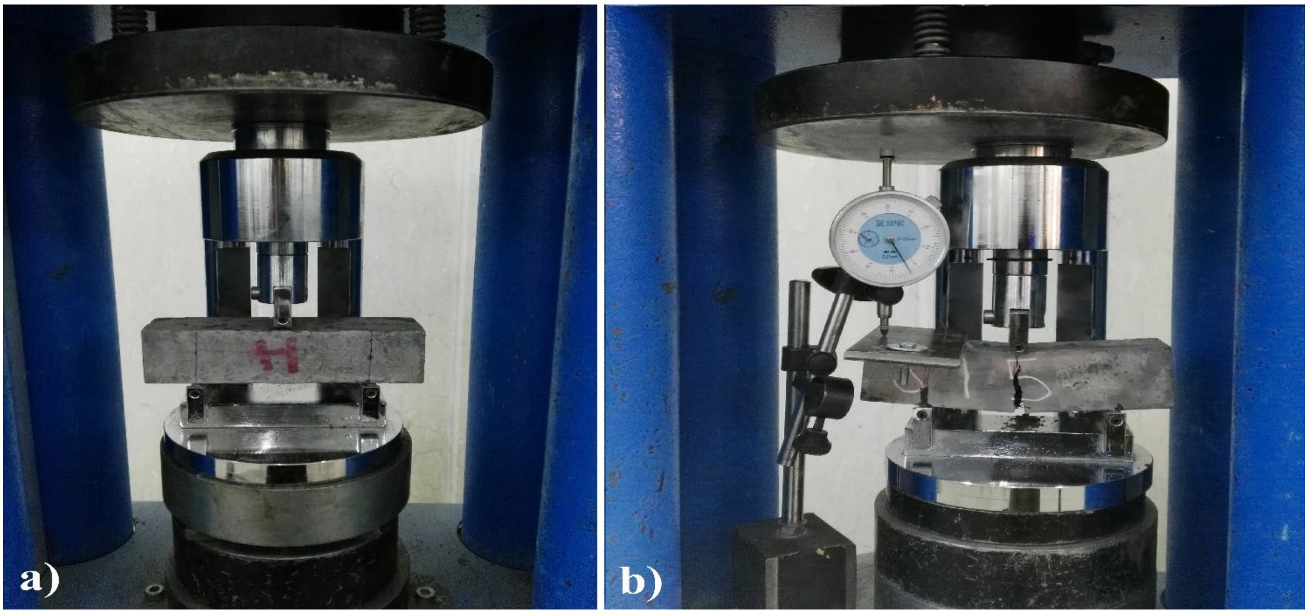

Fig. 6 - (a) Flexural strength test; (b) flexural toughness test

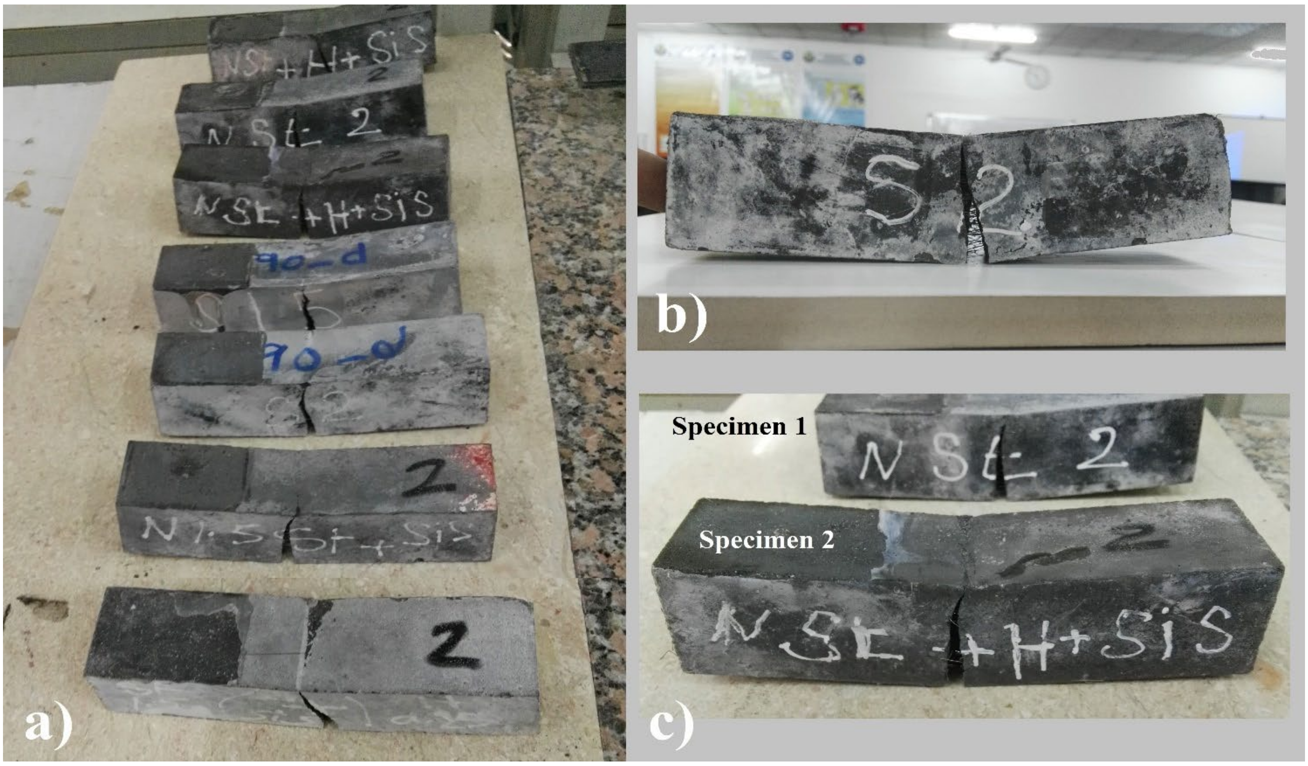

Fig. 7 - Failure mode after bending tests; (a) Some tested specimens of RPC; (b) The specimen of mix MS; (c) The specimen 1 of mix MNS, the specimen 2 of mix MNH3

Table 4 - Mix proportion of RPC mixes used in this research*

Mix	OPC	GP	ISP	SF	Sand	NG	NS	HHF %	SIF %	MSF %
M0	693	79	119	99	990	0	0	0	0	0
MS	693	79	119	99	990	0	0	0	0	2
MH1	693	79	119	99	990	0	0	0	0.5	1.5
MH2	693	79	119	99	990	0	0	0.5	0	1.5
MH3	693	79	119	99	990	0	0	0.25	0.25	1.5
MNS	693	79	119	99	990	25	25	0	0	2
MNH1	693	79	119	99	990	25	25	0	0.5	1.5
MNH2	693	79	119	99	990	25	25	0.5	0	1.5
MNH3	693	79	119	99	990	25	25	0.25	0.25	1.5

*The quantity of materials were calculated in kg/m^3 and rounded to the nearest of 1 kg/m^3.

Table 5 - Flowability of the mixes used in this study

	RPC mixes								
	M0	MS	MH1	MH2	MH3	MNS	MNH1	MNH2	MNH3
Flow value, mm	230	223	222	225	224	220	220	222	221

Table 6 - Compressive strength of RPC samples

Mix	NG %	NS %	HHF %	SIF %	MSF %	Compressive strength, MPa		
						7 days	28 days	90 days
M0	0	0	0	0	0	81.78	87.21	90.32
MS	0	0	0	0	2	85.53	93.01	96.43
MH1	0	0	0	0.5	1.5	84.71	91.02	95.01
MH2	0	0	0.5	0	1.5	84.25	90.77	94.83
MH3	0	0	0.25	0.25	1.5	85.02	92.01	95.18
MNS	2.5	2.5	0	0	2	97.84	115.88	120.21
MNH1	2.5	2.5	0	0.5	1.5	93.59	110.86	115.21
MNH2	2.5	2.5	0.5	0	1.5	91.53	107.34	113.05
MNH3	2.5	2.5	0.25	0.25	1.5	96.64	112.62	118.19

Table 7 - Tensile strength of RPC samples

Mix	NG %	NS %	HHF %	SIF %	MSF %	Tensile strength, MPa	
						28 days	90 days
M0	0	0	0	0	0	3.72	4.66
MS	0	0	0	0	2	4.30	5.24
MH1	0	0	0	0.5	1.5	4.24	5.17
MH2	0	0	0.5	0	1.5	4.22	5.15
MH3	0	0	0.25	0.25	1.5	4.29	5.20
MNS	2.5	2.5	0	0	2	5.20	6.34
MNH1	2.5	2.5	0	0.5	1.5	4.88	5.84
MNH2	2.5	2.5	0.5	0	1.5	4.71	5.60
MNH3	2.5	2.5	0.25	0.25	1.5	5.02	5.91

Table 8 - Flexural strength of RPC samples

Mix	NG %	NS %	HHF %	SIF %	MSF %	Flexural strength, MPa		
						7 days	28 days	90 days
M0	0	0	0	0	0	13.84	15.70	17.01
MS	0	0	0	0	2	16.87	18.74	19.45
MH1	0	0	0	0.5	1.5	16.64	18.48	19.32
MH2	0	0	0.5	0	1.5	16.18	18.12	19.01
MH3	0	0	0.25	0.25	1.5	16.71	18.52	19.40
MNS	2.5	2.5	0	0	2	19.21	22.79	24.44
MNH1	2.5	2.5	0	0.5	1.5	18.74	20.88	21.56
MNH2	2.5	2.5	0.5	0	1.5	18.01	20.15	20.62
MNH3	2.5	2.5	0.25	0.25	1.5	18.98	21.35	22.02

Table 9 - Flexural toughness parameters of RPC

Mix	Fibers, %			ASTM C1609							
	MSF	SIF	HHF	P_L [2]	P_D [3]	P_{600} [4]	P_{150} [4]	F_{600} [5]	F_{150} [5]	T_{600} [6]	T_{150} [6]
M0	0	0	0	7.26	0.28	-	-	-	-	-	-
MNS	2	0	0	10.43	0.40	2.78	8.10	6.52	18.98	0.23	3.99
MNH1	1.5	0.5	0	9.2	0.35	2.51	6.17	5.87	14.46	0.21	3.48
MNH2	1.5	0	0.5	8.8	0.34	2.93	5.76	6.85	13.48	0.22	3.42
MNH3	1.5	0.25	0.25	9.4	0.38	3.18	6.83	7.44	16.01	0.23	3.71

*[1] **Mix** is contained 2.5%NG+2.5%NS except M0. [2] $\mathbf{P_L}$ is first crack load(kN). [3] $\mathbf{P_D}$ is first crack deflection(mm). [4] $\mathbf{P_{600}}$ and $\mathbf{P_{150}}$ is the residual load (KN). [5] **F** is the residual strength (MPa). [6] T is the area under the load vs. net deflection curve (Joule).

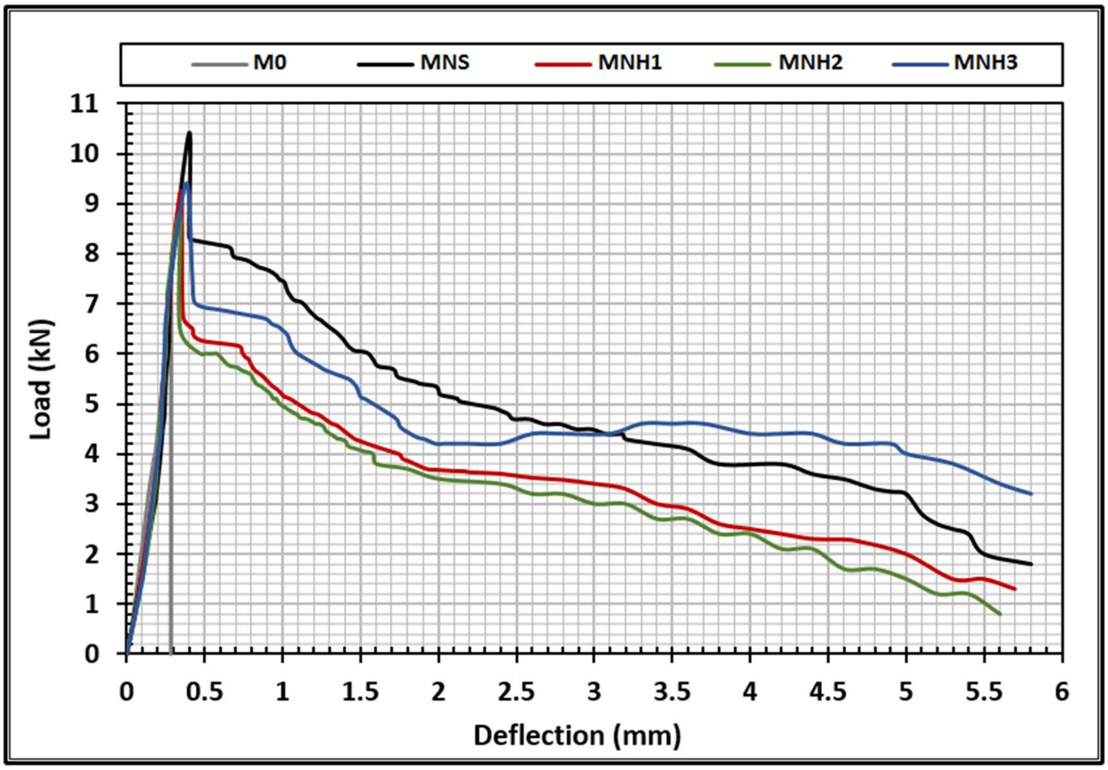

Fig. 8 - Flexural toughness of RPC reinforced with fibers and nanoparticles at 90 days

Table 10 - Modulus of elasticity for RPC samples at age of 90 days

Mix	Static modulus of elasticity (GPa)
M0	34.80
MNS	40.21
MNH1	38.53
MNH2	37.51
MNH3	39.01