



Research Article

Evaluating effects of granulated glass on structural and seismic behavior of tall RC structures using experimental tests and 3D modeling

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ABSTRACT

The use of waste materials for reinforcement of reinforced concrete (RC) structures is of great importance for both environmental cleaning and recycling. In this study, the effects of granulated glass released by factories on the structural behavior of RC structures are examined in detail. Initially, 5 different concretes are produced using 5 different granulated glass percentages. Granulated glass is used instead of aggregate. Different aggregate ratios of granulated glass are taken into account for each sample. 5 different concrete samples are subjected to the slump test and the consistency of the concrete samples is assessed in detail. Then, each concrete sample is subjected to compressive strength tests. It is clearly seen from the compressive strength tests that granulated glass increased the strength of the concrete noticeably. Then, the 31-story reinforced concrete structure is modeled considering the most critical granulated glass ratio. The 1995 Kobe earthquake is utilized for the seismic analyses. Firstly, the RC structure is analyzed for the pure concrete and then, analyses are performed for various granulated glass added cases. According to the analysis results, granulated glass significantly increased the earthquake resistance of reinforced concrete structures. Furthermore, waste granulated glass caused enormous reductions in the weight of the structure. In this study, it is concluded that granulated glass material, which is found in nature as waste, can be used for the construction of RC structures.

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1. Introduction

Ensuring the earthquake safety of tall reinforced concrete (RC) structures is very important for the safety of the people living in these structures. In the past, many methods have been used to strengthen RC structures and one of these methods is to use additives in the concrete. One of these additives is granulated glass and granulated glass is released from factories as waste material to nature. When the literature is examined, it is seen that granulated glass is rarely not used for earthquake reinforcement of RC structures. For this reason, in this study, the effects of granulated glass on the earthquake safety of tall RC structures are investigated in detail. Many

studies have been carried out on the earthquake strengthening of RC structures in the literature. Shen et al. (2021a) examined the seismic behavior of the RC building joints using the basalt fiber-reinforced polymer sheets. Firstly, five various column-beam joints were prepared considering all original specimens. In the experimental loading process, the horizontal displacements and loads applied on the test specimens were monitored, and the cracks were signed at the surface in each cycle. According to experimental tests, it was seen that generally, the seismic behavior of beam-column joints was increased by these five strengthening schemes. For specimen SBC2, better performance of ductility and energy dissipation capacity could be obtained

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by strengthening the interior beam-column joints with the whole lengths of the beams and column in the practical RC frames. Shen et al. (2021b) assessed the flexure and crack behavior of the RC buildings utilizing fabric reinforced Alkali-Activated Slag matrix. The crack patterns and failure modes of the RC beams with and without strengthening were evaluated in detail. According to experimental tests, the control specimen failed in a typical flexural mode for a ductile concrete beam. Moreover, cracks first appeared in the tensile zone at the mid-span of the beams. The yielding of longitudinal reinforcements subsequently occurred as the deflection increased, followed by the crushing of concrete in the compression zone. Tests showed that specimen B-O-S-A0 exhibits a slight improvement in loading capacity over the control specimen at the yielding stage, followed by a sudden drop in load due to the premature end-debonding at the concrete-matrix interface. Nanda et al. (2020) investigated the effects of metakaolin and Recron 3s fiber on the structural behavior of concrete material. Metakaolin was used as a partial replacement for Portland slag cement (PSC). Compressive strength was examined for separate mixtures prepared from the different % replacement of metakaolin (5%, 10%, and 15%) and fly ash (10%, 20%, and 30%) by weight of cement with a constant 0.2% of Recron 3s fiber. Experimental tests showed that blending of metakaolin, fly ash and Recron 3s fiber enhance the overall mechanical properties of concrete. However, with only metakaolin replacement, the best replacement was found to be 10% by weight of cement and the enhancement of compressive strength, split tensile strength and flexural strength was estimated to be 10.25%, 9.46%, and 12.34% respectively at 28 days curing. Wu et al. (2020) assessed the application of bacterial spores coated by a green inorganic cementitious material for the self-healing of concrete cracks. Firstly, the properties of the biocapsule were analyzed and the effect of its dosage on cement mortar properties was evaluated. Then, crack-healing efficiency and water permeability were evaluated to assess the effectiveness of the biocapsule in crack self-healing. According to experimental tests, the addition of biocapsules at a dosage of 5% of the cement mass led to full healing of 150–550 μm width cracks. Furthermore, it was seen that when the biocapsule dosage was less than 5%, the strength of concrete specimens increased with an increase in dosage. Tang et al. (2020) examined the seismic behavior of the fly ash/slag-based geopolymeric recycled aggregate concrete under both quasi-static and dynamic loadings. The experimental tests showed that the compressive properties of geopolymeric recycled aggregate concrete exhibit a strong strain rate dependency. Besides, although the recycled aggregate replacement decreases the quasi-static compressive strength, it exhibits a slight effect on the compressive strength at high strain rates. Then, empirical dynamic increase factor formula for compressive strength of geopolymeric recycled aggregate concrete are proposed, in which the dynamic increase factor increases approximately linearly with the strain rate in a logarithmic manner. Ramdani et al. (2019) assessed the structural properties of concrete material with waste rubber aggregate, glass powder, and silica sand powder.

Various rubber aggregate ratios (10%, 20%, 40%, and 60%) were utilized to replace crushed sand in concrete mixes. Moreover, glass powder and natural sand powder were considered to replace 15% of the cement weight. Nine different forms of concrete with separate wastes and with the combination of them were designed and prepared. The experimental results showed that the strength increased with the incorporation of glass powder and rubber aggregates, especially with 10% and 20% Rubber aggregate contents. Güneyisi et al. (2019) investigated the fresh and rheological properties of glass fiber reinforced self-compacting concrete with nano-silica and fly ash blended. Fifteen mixtures of self-compacting concrete fortified by glass fibres with dissimilar quantities of pozzolanic replacement cement were prepared in a constant water-binder ratio of 0.35 and a total binder content of 550 kg/m^3 . The results showed that self-compacting concrete with replacement of 2% and 4% NS and maximum amount of GF achieved the lower rate of workability enhancement. Zhang et al. (2019) evaluated the mechanical behavior of seawater sea-sand recycled coarse aggregate concrete columns under axial compressive loading. The experimental results showed that the seawater-sea-sand-based concrete column behaves similarly to conventional natural aggregate concrete when the shell content in sea-sand equals 2.31%. Xie et al. (2018) examined the effects of the addition of silica fume and rubber particles on the compressive behavior of recycled aggregate concrete with steel fibres. The silica fume and rubber contents were the main test parameters. It was seen that rubberized steel-fiber recycled aggregate concrete with 100% recycled coarse aggregate, 10% silica fume, and 5% rubber is a more environmentally friendly alternative to normal concrete for use in the compression member of concrete structures. Dash and Patro (2018) assessed the effects of water-cooled ferrochrome slag as fine aggregate on the properties of concrete. Compressive strength tests, splitting tensile strength tests, flexural strength, and modulus of elasticity tests were conducted on various concrete samples containing 0–50% of the water-cooled ferrochrome slag on replacement of equal weight of natural sand. The experimental test results showed that there is a little decrease in strength properties of concrete due to the inclusion of the water-cooled ferrochrome slag but can be used up to 30% with minor scarification of strength. Thorneycroft et al. (2018) evaluated the performance of structural concrete with recycled plastic waste as a partial replacement for sand. The results indicated that replacing 10% sand by volume with recycled plastic is a viable proposition that has the potential to save 820 million tonnes of sand every year. Mohajerani et al. (2017) assessed the practical recycling applications of crushed waste glass in construction materials. According to a review study, it was seen that crushed waste glass has potential use as an aggregate in construction materials. Then, there are many studies about the strengthening of reinforced concrete buildings using waste materials (such as waste granulated glass, industrial lathe wastes) in the literature such as Tamburini et al. (2017), Lynn et al. (2015), Refai et al. (2015), Younis and Pilakoutas (2013), Boukendakdji et al. (2009), Frazão et al. (2019),

El-Sayed (2019), El-Sayed (2021), El-Sayed and Shaheen (2020), El-Sayed et al. (2019a), El-Sayed et al. (2019b). As seen from these studies, the effects of waste granulated glass material on the seismic behavior and strengthening behavior of reinforced concrete structures have not been examined in the past. Thus, this study is of great importance to fill this gap in the literature. In this study, firstly, 5 different ratios of the granulated glass material are used instead of aggregate in concrete material. Concrete samples prepared in the laboratory are subjected to compressive strength tests and the effects of granulated glass utilized in concrete on concrete strength are determined. After the most critical granulated glass ratio is determined, this granulated glass ratio is considered for the concrete material of a 31-story RC structure. Then, reinforced concrete structure with a pure concrete structure and reinforced concrete structure with granulated glass are subjected to earthquake analyses and according to the earthquake analysis results, the effects of granulated glass on the earthquake behavior of reinforced concrete buildings are determined in detail. Experimental and numerical results show whether the granulated glass material left to nature as waste can be used in RC structures.

2. Material and Method

In this study, the effects of granulated glass released as waste material by factories on the seismic behavior of reinforced concrete structures are revealed. When the literature is examined, it is seen that there are very few researchers studying the effects of granulated glass on the earthquake behavior of reinforced concrete structures, and this study aimed to eliminate these deficiencies in the literature. In this study, firstly, concrete samples with 5 different additives are prepared. Granulated glass is used instead of aggregate in concrete samples. After the pure concrete is prepared, concretes with granulated glass are formed by using 5%, 10%, 15%, and 25% rates instead of the aggregate in the concrete. 3 different samples are prepared for each concrete with additives and slump tests are carried out to obtain the consistency of these concretes. Slump tests are performed following the standards and very large consistency differences are observed between the additive concrete and pure concrete. Then, these additive concrete samples are kept in water for 7 days, 14 days, and 28 days. Concrete specimens that reached sufficient hardness are subjected to compressive strength tests. During the compressive strength tests, the dimensions of the samples, the test starting speed, and the correction rate are defined to the device. After the pressure tests are performed, the time-dependent strength graphs of each glass powder added to the concrete are acquired. According to the test results, very large strength differences are observed between the additive concretes and pure concrete. Then, a 31-story reinforced concrete structure is modeled by considering the most critical granulated glass ratio. Modeling is performed using SAP2000 software and the finite element method is utilized in the seismic analysis. All the load-

bearing elements of the building (beam, column, and floor) are created by considering the original project of the building. A fix boundary condition is defined at the base of the structure. In earthquake analysis, the 1995 Kobe earthquake is used. Furthermore, X, Y, and Z components of each earthquake are taken into account for earthquake analyses. The nonlinear situation is considered in the dynamic analyses. The structure is first analyzed for the case modeled with pure concrete. Then, the structure modeled with granulated glass added concrete is subjected to earthquake analyses. According to the analysis results, it is concluded that the use of granulated glass has positive effects both on the earthquake behavior of reinforced concrete structures and on recycling.

3. Mechanical Properties of Waste Granulated Glass

In developing industrial facilities, a very high increase is seen in industrial wastes due to effects such as the increase in population (Uzun et al. 2018). The storage, disposal, or reuse of these wastes has become an important research topic. Waste glass, like other industrial wastes, is difficult to dissolve and has high recycling costs. On the other hand, the fact that it is rich in silica and that there is a lot of waste around the world makes the waste glass more important. Glass production takes place by cooling high-temperature calcium carbonate, soda ash, and molten silica while solidification takes place without crystallization (Uzun et al. 2018). Worldwide waste is estimated to be 200 million tons in 2004, of which 7% consists of glass products. In 2013, 11.54 million tons of waste glass were generated in the USA alone, and only 27.3% of it was recycled. It is widely used in the reinforcement of many composites such as glass, fiber, and aggregate (Uzun et al. 2018). Many studies have been conducted on the use of glass waste in different ways, such as aggregate in concrete, as a filler, as an alkali-activated binder, and as an additive to cement. Thanks to the pozzolanic feature of waste glass, it allows use in concrete. Some trials have been made as concrete aggregate, but the cracks on the concrete surface have created negativity (Uzun et al. 2018). More positive results were obtained in the studies carried out to use the granulated glass as an additive to the cement by grinding it under 0.005 mm size. Many studies have been carried out to increase strength and durability, especially as a result of using it as an additive to cement. The purpose of using waste granulated glass as an additive to cement is to benefit from the silica it contains. Granulated glass provides additional advantages thanks to its pozzolanic feature (Uzun et al. 2018). Granulated glass reacts with portlandite ($\text{Ca}(\text{OH})_2$) formed during cement hydration of amorphous silica (SiO_2) in the granulated glass to form calcium silica hydrate (C-S-H) structures. The reactions of the waste granulated glass used are given below (Uzun et al. 2018).

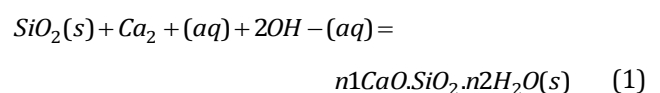




Fig. 1. View of granulated glass (Uzun et al. 2018).

4. Preparation of Concrete Samples

In this study, the effects of granulated glass, which is found as waste in nature, on the earthquake behavior of reinforced concrete structures are investigated in detail. For this reason, first of all, waste granulated glass added concrete cube samples are created in the laboratory. In the laboratory, 5 various cube concrete samples are created in detail. Firstly, pure concrete cube samples are generated. To create pure concrete, 10.7 kg cement, 32.2 kg aggregate, 5.2 kg water are used. Then, granulated glass added concretes are produced and 10.7 kg cement, 30.6 kg aggregate, 5.2 kg water, and 1.6 kg granulated glass are utilized to form M1 added to concrete. Furthermore, 10.7 kg cement, 29.02 kg aggregate, 5.2 kg water, and 3.2 kg granulated glass are considered to create M2 added concrete. Then, 10.7 kg cement, 27.4 kg aggregate, 5.2 kg water, and 4.8 kg granulated glass are used to produce M3 added concrete. Finally, 10.7 kg cement, 25.7 kg aggregate, 5.2 kg water, and 6.4 kg granulated glass are taken into account for M4 added to concrete. The materials used in 5 different concrete samples produced in the laboratory are summarized in detail in Table 1. A total of 3 different samples are prepared for each additive concrete (Fig. 2). Fig. 2 shows the view of placing concrete samples with and without additives in the molds. In Fig. 3, the view of the preparation of concrete samples and the mixing of materials in the mixer is shown. A special mixer is used in the laboratory to prepare concrete samples. After preparing 3 different pure concrete, 3 different M1 samples, 3 different M2 samples, 3 different M3 samples, and 3 different M4 samples, the concrete samples are subjected to slump tests. In addition, 3 samples are prepared for each concrete with additives to obtain 7-day, 14-day, and 28-day strengths. The appearance of the slump tests is shown in Fig. 4. According to Fig. 4, slump tests are performed using 2 different methods (Figs. 4a and 4b). Fig. 4c shows how the consistency amounts are measured for concrete samples. In Table 2, 7-day slump test results are presented in detail. According to Table 2, the slump test result obtained for pure concrete is 20

mm. Besides, the amount of slump obtained for M1 concrete is 115 mm. For M2 and M3 concrete samples, 45 mm and 18 mm slump amounts are observed, respectively. Finally, 80 mm slump is acquired for M4 concrete. Moreover, 7-day, 14-day, and 28-day slump test results are shown in Fig. 5 comparatively. According to Fig. 5, it is concluded that the slump obtained for the 7-day concrete samples is greater than the 14-day and 28-day samples. In addition, the lowest slump is obtained for M3 concrete samples for 7-day, 14-day, and 28-day concrete samples. The highest slump is observed for M1 concrete samples. After the prepared concretes are placed in cube samples and subjected to slump tests, the samples are kept in water for 7 days, 14 days, and 28 days (Fig. 6). For this process, a special water pool is used and the water temperature is defined to the device to provide more realistic results. Fig. 7 shows the view of the device used to pressure test concrete samples. Both cube and cylindrical concrete samples can be used in the device used for pressure tests. Furthermore, the dimensions of the samples, correction coefficients, and test speed can be defined in the device during the test. After the test is performed using the device, the results can be printed from the device both with the help of USB and in writing (Fig. 8).

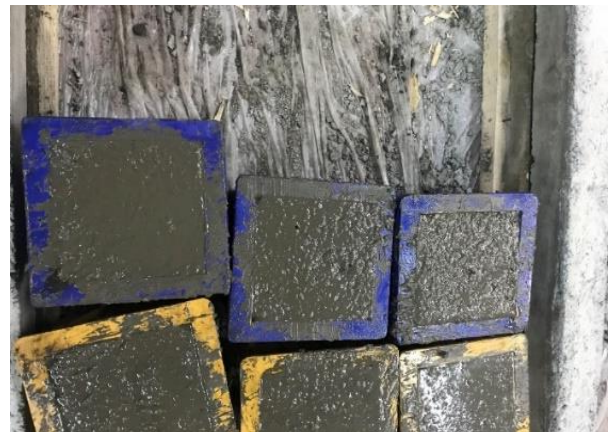


Fig. 2. Preparing concrete molds in the laboratory.

Table 1. Material weights of concrete samples.

Situation	Material	Weight (kg)
Pure Concrete	Cement	10.731
	Aggregate	32.235
	Water	5.250
	Ground Glass	0
M1	Cement	10.731
	Aggregate	30.618
	Water	5.250
	Ground Glass	1.617
M2	Cement	10.731
	Aggregate	29.022
	Water	5.250
	Ground Glass	3.234
M3	Cement	10.731
	Aggregate	27.405
	Water	5.250
	Ground Glass	4.830
M4	Cement	10.731
	Aggregate	25.788
	Water	5.250
	Ground Glass	6.447

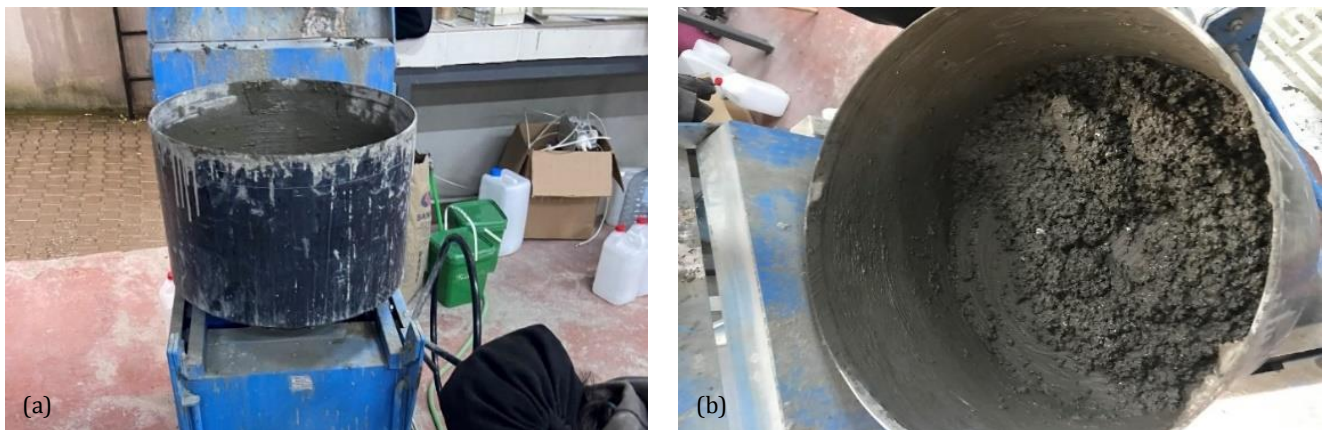
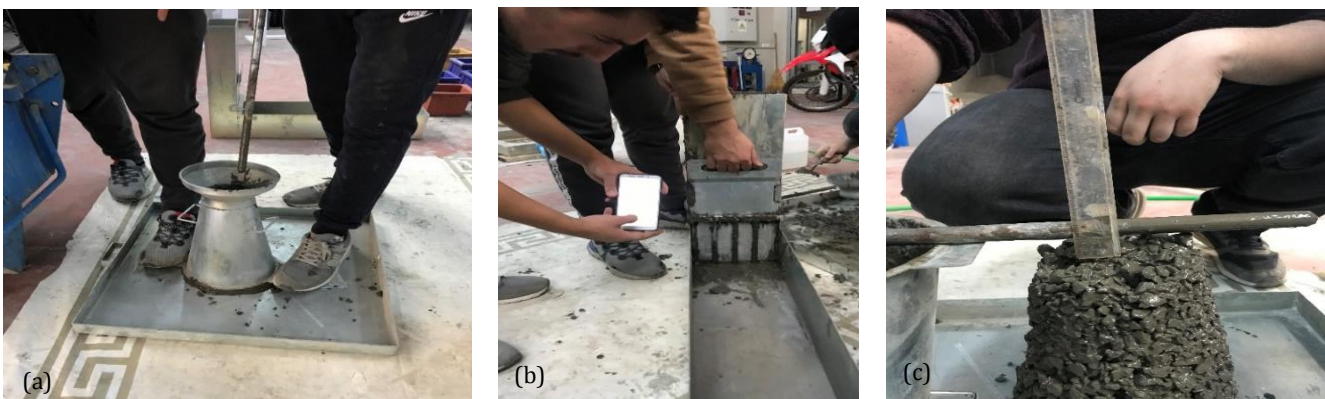
**Fig. 3.** Mixing of materials for creating concrete sample.**Fig. 4.** Views of various slump tests.

Table 2. Slump test results of concrete samples.

Mix	Ground Glass (%)	Slump Value (mm)
Pure Concrete	0	20
M1	5	115
M2	10	45
M3	15	18
M4	20	80

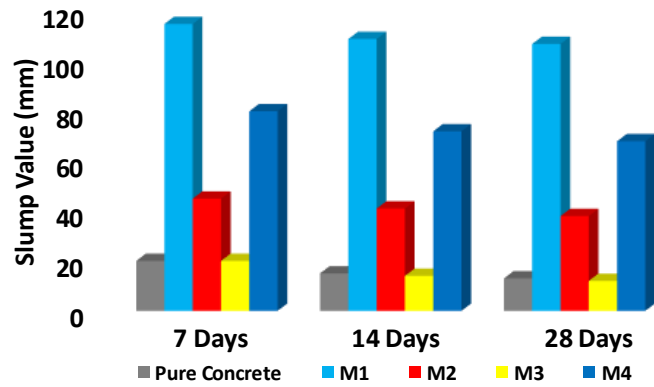


Fig. 5. Detailed slump test results.



Fig. 6. Keeping the concrete samples in the water pool.



Fig. 7. General view of the prepared concrete samples.



Fig. 8. Using the compressive strength device.

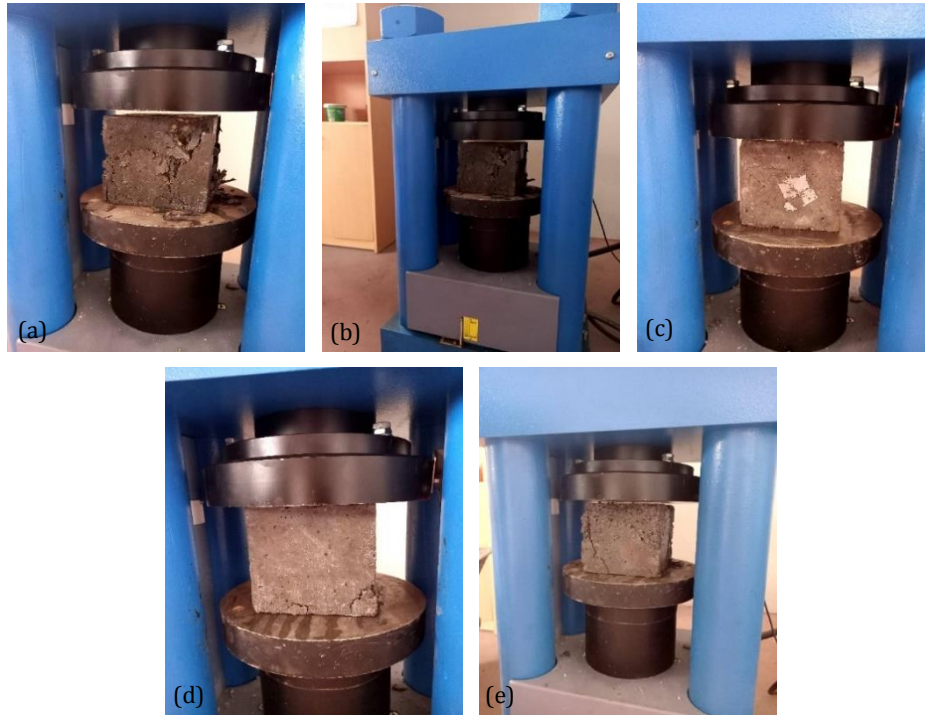


Fig. 9. View of concrete samples during compressive strength test: a) Pure concrete; b) M1 sample; c) M2 sample; d) M3 sample; e) M4 sample.



Fig. 10. View of all concrete samples subjected to compressive strength test (for 7 days).

Fig. 9 shows the appearance of 5 different mixed concrete samples subjected to pressure tests. During the experiments, protective clothing was worn to protect human safety. According to the results of the pressure test, it is seen that the granulated glass additive changes the strength of the concrete. Fig. 9a shows the view of the pressure test for pure concrete. According to Fig. 9a, significant cracks and damages occurred in the pure concrete during the test. Fig. 9b shows the view of the pressure test performed for the M1 sample. According to Fig. 9b, it is seen that the cracks occurring in 5% granulated glass added concrete is more than in pure concrete. In addition, the concrete test results acquired for the M2 sample are shown in Fig. 9c. When Figs. 9b and 9c are compared with each other, it is openly seen that the cracks that took place in the concrete sample are less for

M2 concrete. In Figs. 9d and 9e, the compression test results obtained for the M3 and M4 samples are shown and it is observed that the concrete cracks obtained for the M3 and M4 samples are more than the M2 sample. In Fig. 10, the appearance of the 7-day concrete samples subjected to the compressive strength test is shown. When Fig. 10 is examined in detail, it is clear that the largest cracks occurred for pure concrete. Furthermore, it is observed that the smallest concrete cracks are gained for the M2 sample. In Table 3, the test results of concrete samples subjected to the compressive strength test are shown in detail. When Table 3 is assessed, the maximum carrying load value obtained for 3 different pure concrete samples is 428 kN. The smallest carrying load value is 369 kN. Moreover, Table 3 shows the compressive strength test results acquired for the M1 sample and the largest carrying load value obtained for 3 different M1 samples is 478 kN. The compressive test results obtained for the M2 sample are shown. The smallest and largest carrying load values acquired for 3 different M2 samples are 486 kN and 513 kN, respectively. As the compressive test results for M3 and M4 samples are evaluated, it is understood that the maximum carrying load value obtained for the M4 sample is much smaller than that of the M3 sample. When the 7-day concrete samples are compared with each other, it is concluded that the concrete sample with the highest strength is the M3 sample. In addition, it is observed that the concrete sample with the smallest strength is the M4 sample. It is clear from these results that 15% granulated glass added concrete is more durable than pure concrete, and as 5%, 10%, 15%, and 20% granulated glass added rates are compared, it is concluded that the most critical additive rate increasing the strength of pure concrete is 15% granulated glass additive ratio.

Table 3. Compressive strength results for 5 various concrete samples.

		7 Days (kN)	Average	14 Days (kN)	Average	28 Days (kN)	Average
Pure Concrete	Sample 1	418		429		612	
	Sample 2	402	395	434	424	543	579
	Sample 3	367		411		582	
M1 Concrete	Sample 1	482		581		782	
	Sample 2	457	454	517	529	771	758
	Sample 3	423		491		723	
M2 Concrete	Sample 1	515		747		903	
	Sample 2	484	492	732	723	884	879
	Sample 3	478		691		852	
M3 Concrete	Sample 1	431		877		1172	
	Sample 2	401	400	851	857	1052	1050
	Sample 3	368		843		926	
M4 Concrete	Sample 1	285		593		645	
	Sample 2	278	278	576	583	616	628
	Sample 3	271		581		623	

5. Three-Dimensional Finite Element Modeling of Tall RC Building

This study, it is aimed to examine the seismic damage performance of tall RC buildings considering the effects of granulated glass. For this purpose, a 31-story RC building is selected for 3D modeling and SAP2000 software based on the finite element method is utilized during modeling of this RC structure. Since detailed damage analysis of structures can be made with this program, the SAP2000 program is used in the study. This RC structure has a total of 4 flats on one floor. While modeling this RC structure, 6 different columns are defined to the software, and the sizes of these columns are defined as 30x50 cm, 40x75 cm, 25x40 cm, 35x60 cm, 30x40 cm, 40x40 cm, respectively. Moreover, there is a circular column in the structure and its diameter is defined as 65 cm. Then, the sizes of beams used in the three-dimensional model are defined as 25x35 cm, 30x60 cm, and 30x50 cm, respectively. The class of concrete columns and beams is defined as C25 and this value is gotten from the original structure project. In the RC structure, there is 1 shear wall and its thickness is 25 cm. Besides, the thicknesses of the floor covering are 25 cm and 20 cm for all floors. The height of each floor is 3 m and there are a total of 31 floors in the structure. In this study, the seismic behavior of the structural elements of the building is investigated and the foundation section is not modeled and fixed elements are defined on the base of the structure. Firstly, structural components are created according to the original structure project. While modeling structural components, the mass source is defined to software using dead and live loads. Furthermore, rigid diaphragms are created in the structure considering the constraint z-axis. Then, nonlinear time history analyses are performed according to the direct integration solution type. For this purpose, the Hilber-Hughes-Taylor method is

taken into account in the 3D analyses and its gamma and beta value is selected as 0.5 and 0.25, respectively. 3D model of the structure is shown in Fig. 11.

6. Three-Dimensional Finite Element Analysis Results

In this study, the effects of granulated glass material, which is waste in nature, on the earthquake behavior of tall reinforced concrete buildings are discussed. After a total of 5 different concretes (pure concrete, M1, M2, M3, and M4 concretes) are prepared, the strengths of these concretes are determined. Considering these strength results, a 31-story high reinforced concrete structure is modeled as three-dimensional. The SAP2000 program-based finite-element method is used to model the building. After the structure is modeled, 5 different earthquake analyzes are performed using the 1995 Kobe earthquake. The magnitude of the 1995 Kobe earthquake is 6.9 Mw. Also, the distance of the earthquake is 0.6 km, the A_p value is 0.82g, the V_p value is 81.0 cm/s, and the T_p value is 0.9 s. Earthquake accelerations, directions, analysis type, time interval are defined to the program and earthquake analysis is started. Firstly, the modal analyzes of the structure are made and the results presented in Fig. 12 are obtained. According to Fig. 12, it is openly seen that the modal analyzes of the building are performed for 5 different concrete types. According to Fig. 12a, if pure concrete is used for the carrier elements of the structure, the natural frequency value of the structure becomes 0.285 Hz. As Fig. 12b is examined in detail, it is seen that the natural frequency value of the structure is 0.332 Hz. When this value is compared with the result obtained for the pure concrete structure, it is concluded that the M1 concrete significantly increases the natural frequency value of the structure. In Fig. 12c, the

modal behavior of the structure analyzed using M2 added concrete is presented. According to Fig. 12c, the natural frequency value acquired for the structure analyzed using M2 concrete is 0.427 Hz. As the M1 concrete with structure is compared with the M2 concrete with structure, it is understood that the M2 concrete (10% granulated glass) affects the modal behavior of the structure more. In

Fig. 12d, the modal behavior of the structure analyzed with M3 concrete is presented. According to Fig. 12d, the natural frequency value gained in the structure analyzed using concrete with M3 additives is 0.591 Hz. Finally, when Fig. 12e is assessed in detail, it is seen that the natural frequency value that took place in the structure analyzed using concrete with M4 additives is 0.302 Hz.

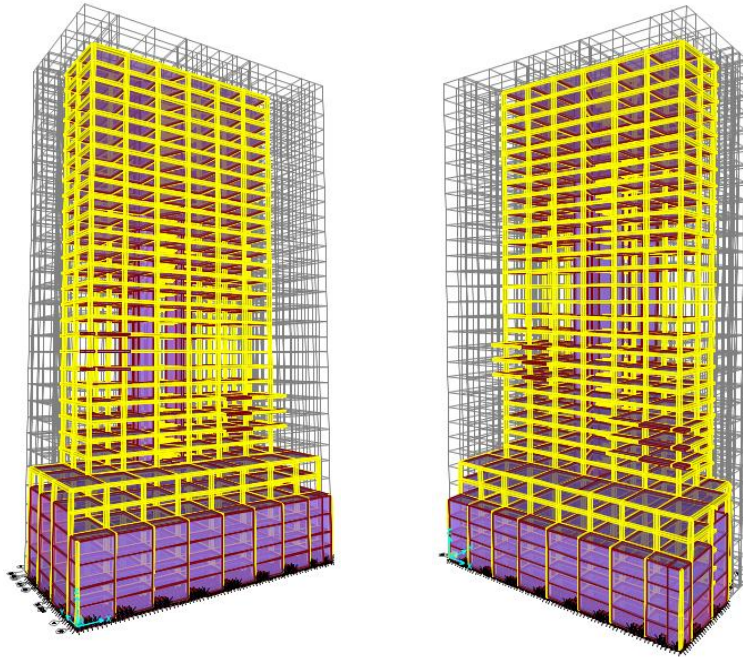


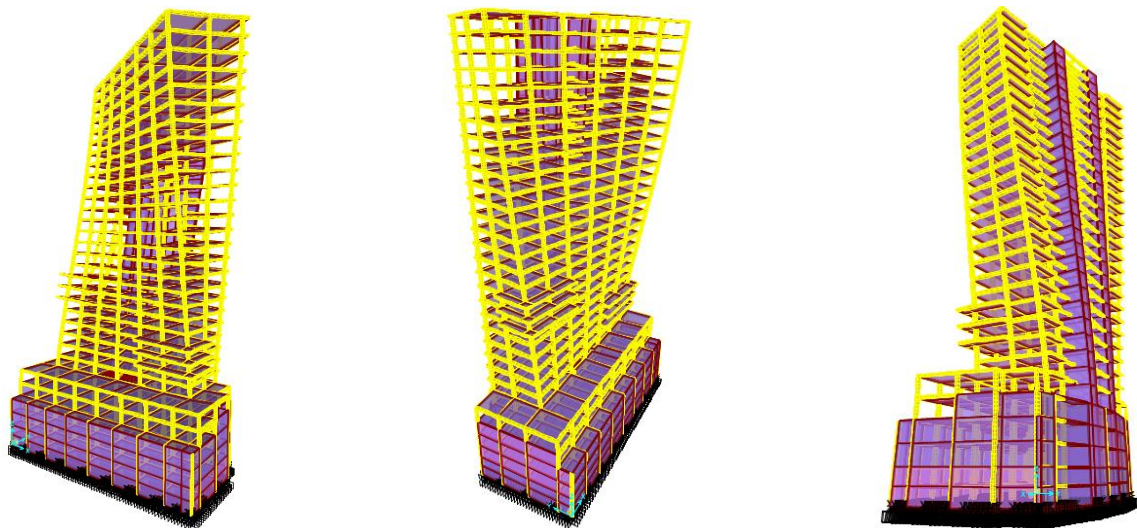
Fig. 11. Views of 3D model of the RC structure.

When the modal analysis results are compared with each other, it is openly observed that the natural frequency value that occurred in the structure analyzed with pure concrete is less than the others. This result shows that the natural period value acquired in the structure analyzed with pure concrete is higher than in the structures with granulated glass additives. Besides, the largest natural frequency value obtained for the granulated glass added structures are obtained for the structure with M3 concrete. It is clear from this result that M3 concrete has the effect of increasing the modal behavior of reinforced concrete structures more positively when compared to other additive concretes. In Fig. 13, the seismic displacement values of 5 different structures obtained as a result of seismic analyzes are presented in detail. In Fig. 13a, the earthquake analysis results of the structure analyzed with pure concrete are presented. According to Fig. 13a, it is understood that serious displacements occurred in the structure as a result of the earthquake. It is seen that the greatest horizontal displacement value in the building is 46 cm, and it is understood that this displacement took place at the top floor of the building. In Fig. 13b, the seismic analysis results acquired utilizing M1 concrete are shown. According to Fig. 13b, the largest horizontal displacements in the building occurred at the top floor of the building, and the largest horizontal displacement value gained in the building is 32 cm. Moreover, serious deformations occurred on the lower floors of the building. However, as Figs. 13a and 13b are compared with each other, it is

seen that if M1 concrete is used in the building, the structure will deform less during an earthquake. This result shows that granulated glass additive affects the earthquake behavior of tall reinforced concrete buildings positively. Fig. 13c shows the seismic displacement behavior of the structure analyzed using M2 concrete. According to Fig. 13c, the largest horizontal displacement value that occurred in the building during an earthquake is 28 cm. This value took place on the top floor of the building and less seismic deformation is observed when compared to the pure concrete structure. In the structure analyzed using M3 concrete, 15 cm maximum horizontal displacement is observed and this maximum displacement occurred in the middle floors of the building (Fig. 13d). When Fig. 13e is evaluated, it is seen that the maximum horizontal displacement value obtained in the reinforced concrete building, which is analyzed considering the M4 concrete, is 38 cm. When the seismic analysis results obtained for 5 different structures are compared with each other, it is understood that the structure with the lowest displacement value is the structure using M3 concrete. In addition, the structure in which the maximum seismic deformations are obtained is the structure analyzed with pure concrete. It is clear from this result that 15% granulated glass additive affects the seismic behavior of reinforced concrete structures positively. In Figs. 14–18, the seismic M3 behavior of 5 different structures is presented. The seismic M3 values of the structure analyzed using pure concrete are shown in Fig. 14. According to Fig. 14, maximum M3 values are obtained

in the beams on the 4th floor of the building during the earthquake. The maximum M3 values occurred in the beams on the fourth floor of the building are 209 kNm, 238 kNm, and 221 kNm, respectively. In addition, serious M3 values are observed in the beams on other floors. In Fig. 15, the analysis results obtained using M1 concrete are presented. According to Fig. 15, maximum M3 values are observed in the beams on the eighth floor of the building and maximum M3 values of 182 kNm, 197 kNm, and 163 kNm are acquired in the beams on the eighth floor of the building, respectively. On the lower floors of the building, M3 values similar to the eighth floor are observed. In Fig. 16, the earthquake behavior of the structure analyzed using M2 concrete is presented. According to Fig. 16, maximum M3 values are observed in the beams on the seventeenth floor of the building. The maximum M3 values observed in the beams on the seventeenth floor of the building are 94 kNm, 83 kNm, and 75 kNm, respectively. In Fig. 17, the earthquake behavior of the structure analyzed using M3 concrete is shown in detail. According to Fig. 17, maxi-

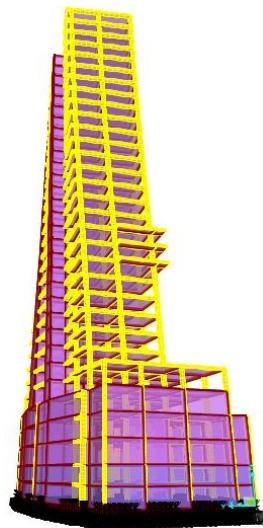
mum M3 values are obtained in the beams on the fourteenth floor of the building and the largest M3 values that took place on the fourteenth floor of the building are 26 kNm, 32 kNm, and 42 kNm, respectively. In Fig. 18, the seismic behavior of the structure analyzed using M4 concrete is presented and the largest M3 values that occurred in the building are observed on the second floor of the building. The maximum M3 values obtained in the beams on the second floor of the building are 195 kNm, 203 kNm, and 211 kNm, respectively. Besides, serious M3 values are observed on the upper floors of the building. As the seismic analyzes of 5 different structures are evaluated, fewer M3 values are obtained in the beams of the analyzed structure using M3 additive concrete compared to other structures. Besides, when 5 different structures are compared, it is understood that the M3 values in the structure using pure concrete are much higher than the other structures. In the structures analyzed with pure concrete and M4 concrete, M3 values close to each other are observed. Summary of results is shown in Table 4.



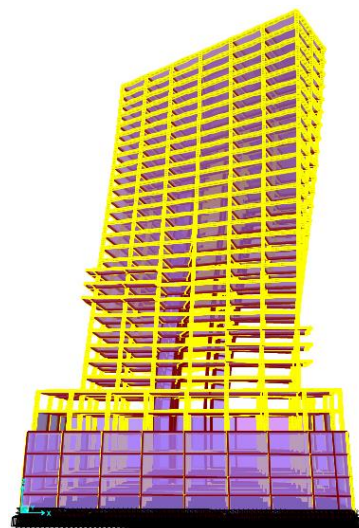
a) Natural Frequency for Pure Concrete: 0.285 Hz

b) Natural Frequency for M1 Concrete: 0.332 Hz

c) Natural Frequency for M2 Concrete: 0.427 Hz



d) Natural Frequency for M3 Concrete: 0.591 Hz



e) Natural Frequency for M4 Concrete: 0.302 Hz

Fig. 12. Modal analysis results.

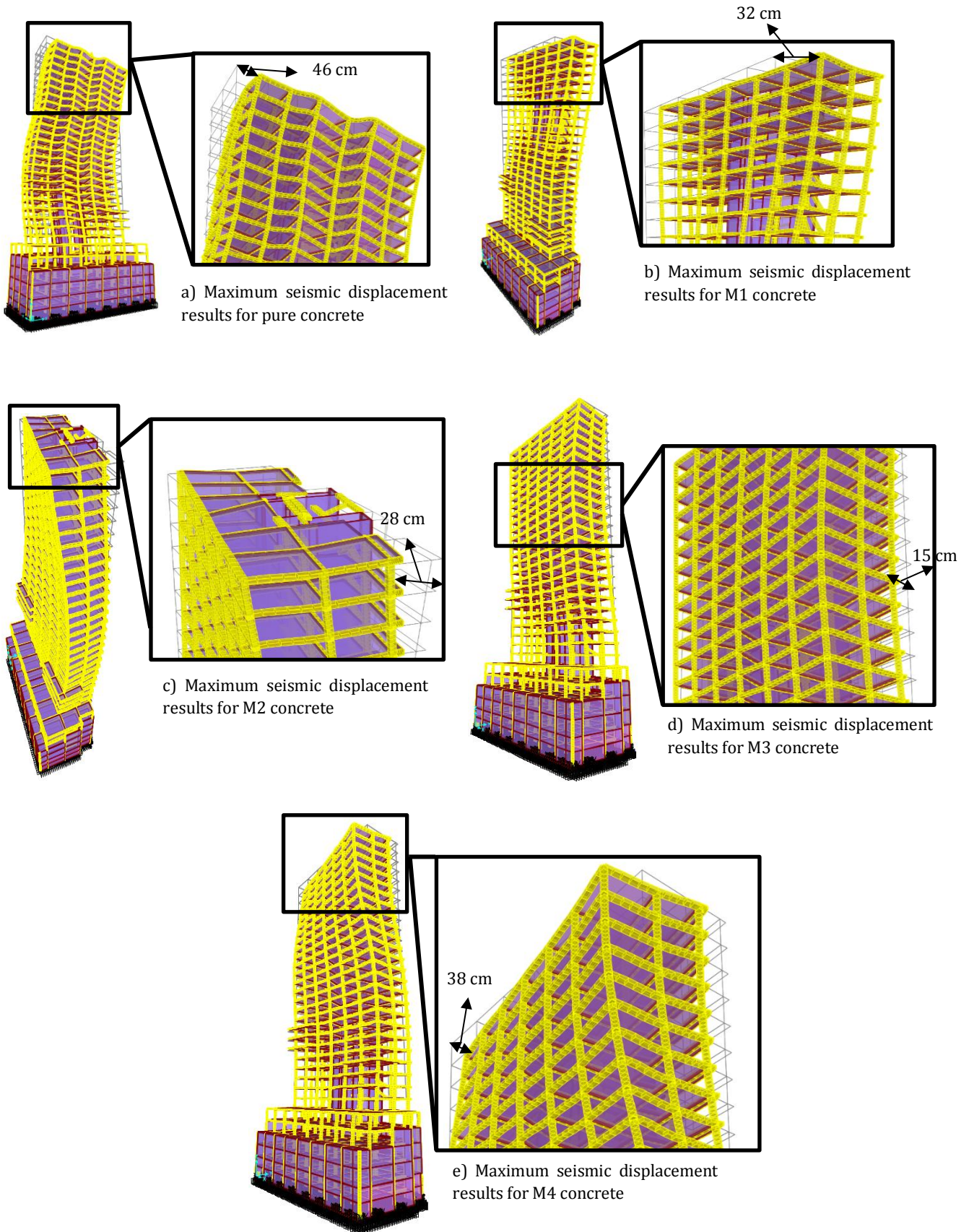


Fig. 13. Seismic displacement results for five various buildings.

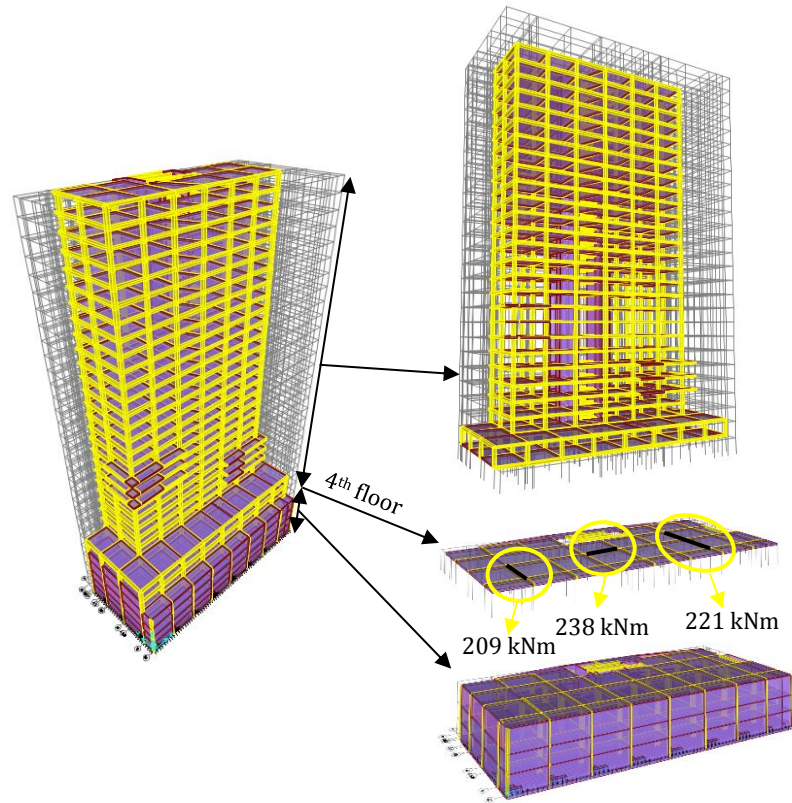


Fig. 14. Seismic principal stress results for pure concrete.

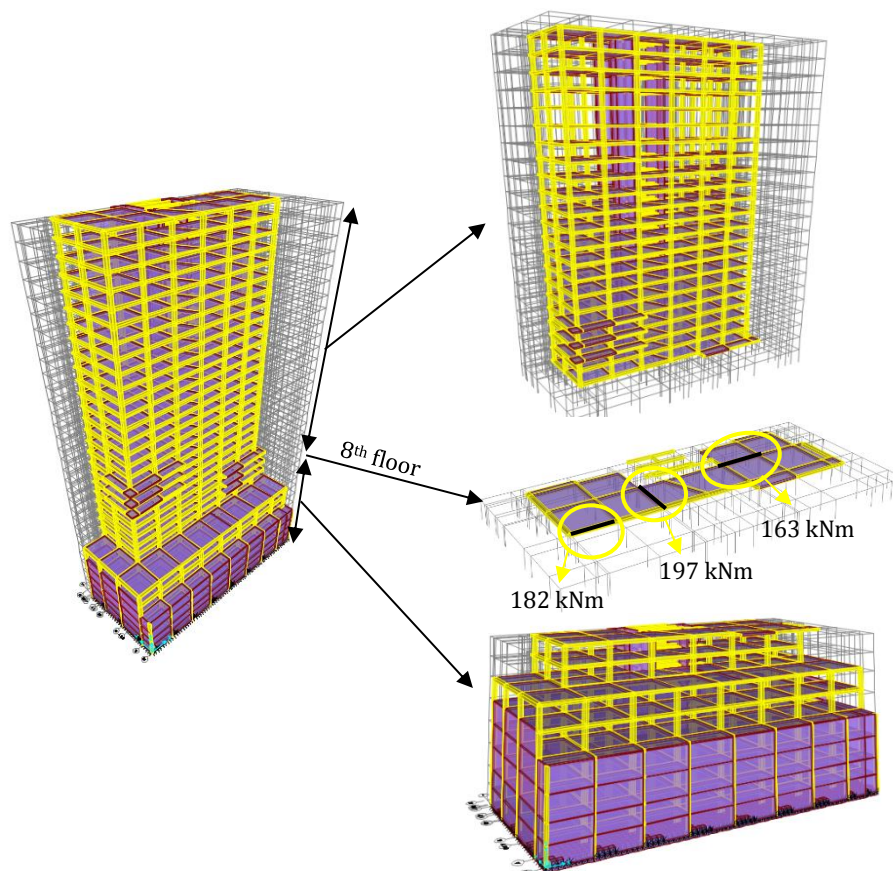


Fig. 15. Seismic principal stress results for M1 concrete.

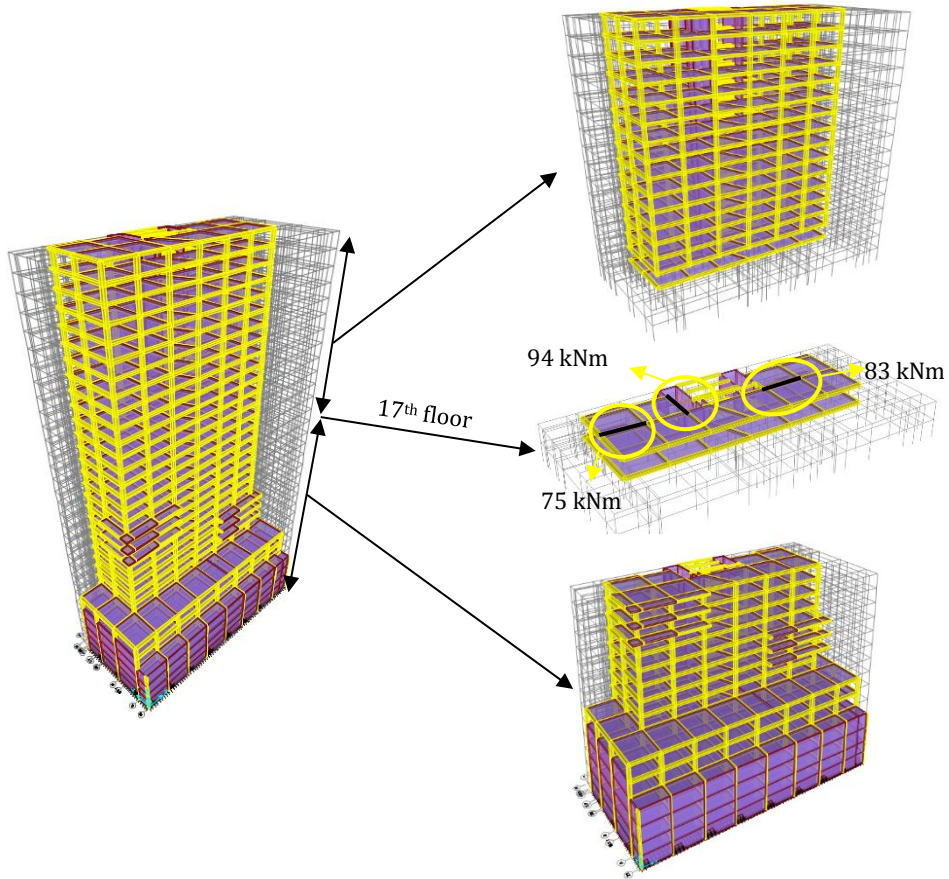


Fig. 16. Seismic principal stress results for M2 concrete.

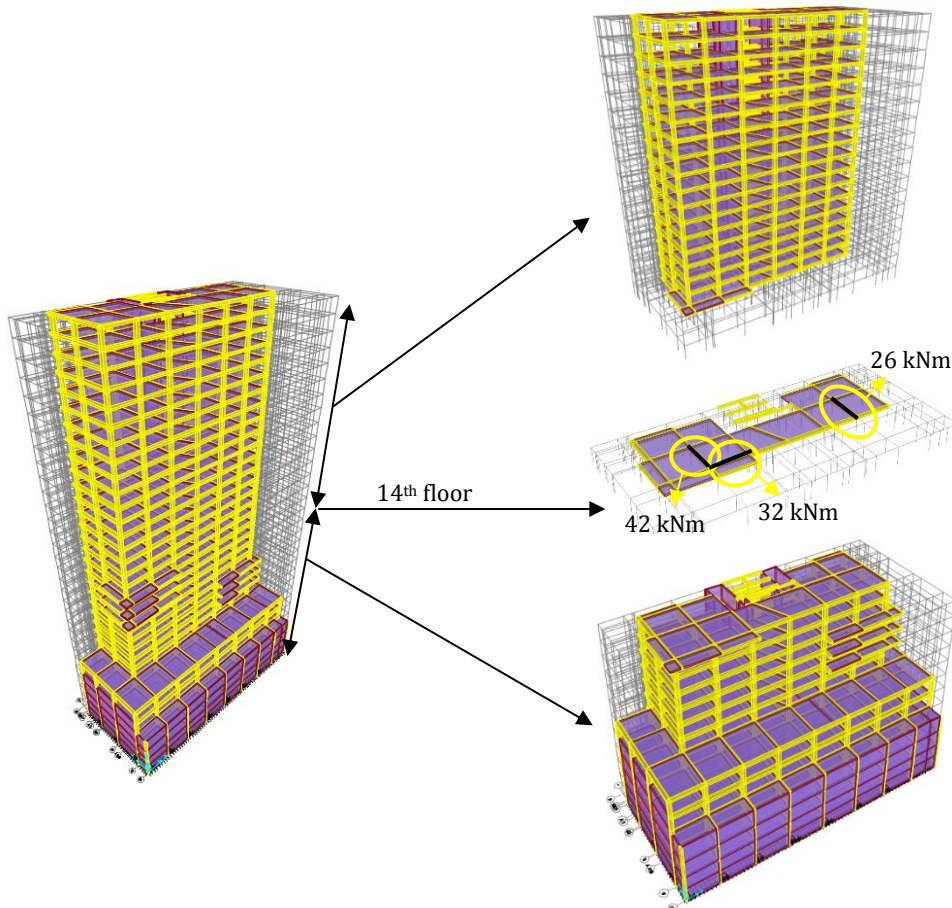


Fig. 17. Seismic principal stress results for M3 concrete.

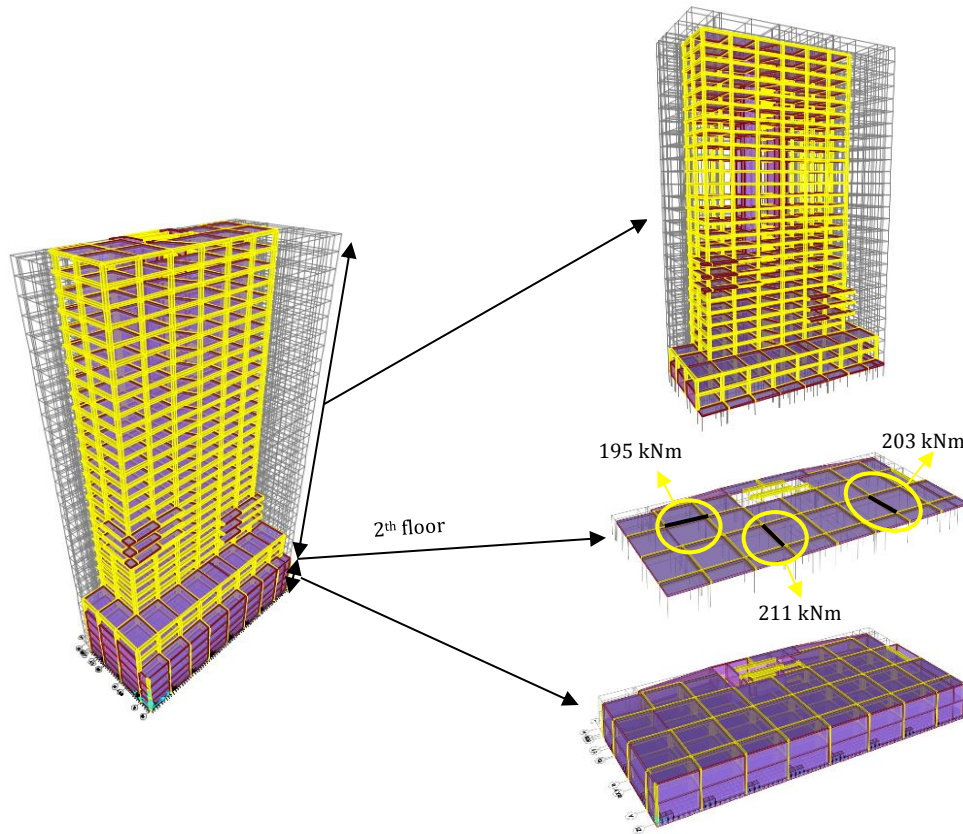


Fig. 18. Seismic principal stress results for M4 concrete.

Table 4. Summary of analysis results.

	Natural Frequency (Hz)	Max Displacement (cm)	Max Principal Stress (kNm)	Weight of Structure (t)
Pure Concrete	0.285	46	238	7267
M1 Concrete	0.332	32	197	7159
M2 Concrete	0.427	28	94	7064
M3 Concrete	0.591	15	42	6912
M4 Concrete	0.302	38	211	6833

7. Conclusions

In this study, the effects of the waste granulated glass material on the earthquake behavior of reinforced concrete structures and whether this waste material can be used in concrete materials of reinforced concrete structures are revealed. Firstly, 7-day, 14-day, and 28-day concrete samples are prepared. Pure concrete, M1 sample, M2 sample, M3 sample, and 3 cube concrete samples each from M4 samples are prepared, and these concrete samples are subjected to a compressive strength test. After the most critical granulated glass ratio is determined, a 31-story reinforced concrete structure is modeled as three-dimensional with the help of SAP2000 software. The most critical granulated glass ratio obtained is defined to the concrete material of the building. Then, the structure is subjected to earthquake analyses both as the most critical granulated glass ratio and pure concrete. 1995 Kobe earthquake is used in earthquake analyses.

According to the results of the experimental and seismic analysis, the following important results are obtained.

- As a result of the experimental tests, it is seen that the granulated glass material used in concrete instead of aggregate for 15% rate increases the strength of the concrete. This result means that the granulated glass material, which is waste in nature, is recycled in the construction industry. The use of granulated glass material in reinforced concrete structures is of great importance for both our nature and our health.
- When the slump tests of pure concrete, 5%, 10%, 15%, and 20% granulated glass added to the concrete are compared with each other, it is seen that the highest amount of slump occurred as a result of the experiment is observed for 5% granulated glass added to concrete. Besides, the smallest amount of slump was obtained for 15% granulated glass added to concrete. From this result, it is understood that 15% granulated glass additive increases the consistency of pure concrete.

- In this study, it is concluded that as the waste granulated glass material is used in reinforced concrete structures, both our nature will be protected and the total weight of reinforced concrete structures will decrease. Because granulated glass material is used instead of aggregate material in concrete and aggregate material is much heavier than granulated glass material. For this reason, it has been concluded that the use of waste granulated glass material in reinforced concrete structures causes serious reductions in building weight.
- When pure concrete, 5%, 10%, 15%, and 20% granulated glass added concretes are taken into account, it is openly seen that the highest damages occurred in the tall reinforced concrete structure, which was subjected to earthquake analysis, are obtained for pure concrete. The smallest moments and displacements observed in the carrier elements of the structure are acquired for 15% granulated glass added to concrete. It is clear from this result that the use of 15% granulated glass in tall reinforced concrete structures provides positive effects in terms of earthquake resistance and earthquake damage of these structures. For this reason, in this study, it is revealed that the use of granulated glass material instead of aggregate material in reinforced concrete structures for 15% rate has positive effects on the earthquake behavior of reinforced concrete structures.

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Conflict of Interest

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