

**EXPERIMENTAL BEHAVIOUR OF SHEAR-CRITICAL
BEAMS PRODUCED FROM GEOPOLYMER CONCRETE**

**JEOPOLİMERİK BETONDAN İMAL EDİLMİŞ KESME
KRİTİK KİRİŞLERİN DENEYSEL İNCELENMESİ**

SERTAÇ UÇAK

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ABSTRACT

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Portland cement consumption tends to grow continuously with the increasing population and developing infrastructure works. It is known that Portland cement production causes a very high energy consumption and is responsible for approximately 8% of human-induced carbon dioxide emissions. At the same time, natural resources are consumed quickly with the production of Portland cement. Considering the damages of Portland cement to nature and the environment, it is of great importance to developing alternative environmentally friendly and sustainable building materials. On the topic of global warming, which has attracted the attention of the whole world in recent years, eco-friendly building materials will be very beneficial to nature.

On the other hand, due to the increasing population, the continuous infrastructure and urbanization cause a large amount of construction and demolition waste. In addition to maintenance and repair works, the significantly increasing urban transformation works leave behind a considerable amount of solid waste. In addition to the environmental damage of these solid wastes, storage in large clean areas is another issue that should be considered. In this context, recycling these construction and demolition wastes in the most beneficial way possible has attracted the attention of the construction industry in recent years. The transformation of construction and demolition wastes into building materials with

appropriate recycling techniques will bring significant economic, social, and environmental benefits.

Considering the harmful effects of Portland cement, interest in the production of aluminosilicate-based materials with alkali activation has increased in recent years. In this context, the most essential material class that stands out is called geopolymer. Geopolymers are produced by the reaction of waste materials with a certain aluminosilicate content with chemical activators such as alkali hydroxide and alkali silicate and have structural and environmental advantages compared to Portland cement concretes. In the literature, there are many studies on the development of geopolymer with materials such as fly ash, silica fume, and blast furnace slag, which are generated as waste materials in the production process of various factories and facilities. As a result of the gradual increase of such waste materials, geopolymer studies are of great importance in order to prevent damage to nature and the environment and to minimize Portland cement production by using it in the development of alternative building materials.

This study aims to develop geopolymer materials as an alternative to Portland cement concrete with the use of construction and demolition wastes, which have been increasing in recent years. Within the scope of the research, the aim is first to develop geopolymer binders with construction and demolition wastes, then to produce geopolymer concrete at a level comparable to Portland cement concretes. In the continuation of the study, it is aimed to compare the results of load-displacement, moment-curvature as a result of four-point bending tests by producing geopolymer beam and reinforced Portland cement beam. The results show that geopolymer beams perform similarly to Portland cement beams. As a result of this study, important outputs have been achieved in developing environmentally friendly and sustainable geopolymer building elements to reduce the harmful effects of Portland cement.

Keywords: Geopolymer Beams, Construction and Demolition Waste, Shear Tests, Concrete Beams, Sustainable Construction

ÖZET

JEOPOLİMERİK BETONDAN İMAL EDİLMİŞ KESME KRİTİK KİRİŞLERİN DENEYSEL İNCELENMESİ

Sertaç UÇAK

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Portland çimentosu tüketimi, artan nüfus ve gelişen altyapı çalışmaları ile birlikte sürekli artma eğilimindedir. Portland çimentosu üretiminin oldukça yüksek bir enerji tüketimine neden olduğu ve insan kaynaklı karbondioksit salınımlarının yaklaşık %8'inden sorumlu olduğu bilinmektedir. Aynı zamanda Portland çimentosu üretimini ile doğal kaynaklar hızlı bir şekilde tüketilmektedir. Portland çimentosunun bu gibi doğa ve çevreye verdiği zararlar göz önünde bulundurulduğunda, alternatif çevre dostu ve sürdürülebilir yapı malzemelerinin geliştirilmesi büyük önem taşımaktadır. Son yıllarda tüm dünyanın ilgisini çeken küresel ısınma konusunda inşaat mühendisliği olarak geliştirilecek çevre dostu yapı malzemeleri doğaya oldukça faydalı olacaktır.

Öte yandan, artan nüfusa bağlı olarak sürekli devam eden altyapı ve kentleşme çalışmaları, büyük miktarda inşaat ve yıkıntı atığı üretilmesine neden olmaktadır. Bakım ve onarım çalışmalarının yanı sıra, önemli ölçüde artan kentsel dönüşüm çalışmaları, arkasında oldukça fazla miktarda katı atık bırakmaktadır. Bu katı atıkların çevreye verdiği zararların yanı sıra, büyük temiz sahalarda depolanması da üzerinde düşünülmesi gereken bir diğer husus olmaktadır. Bu bağlamda bu inşaat ve yıkıntı atıklarının olabilecek en faydalı şekilde geri dönüşümleri son yıllarda inşaat endüstrisinin ilgisini çekmektedir. İnşaat ve yıkıntı

atıklarının uygun geri dönüşüm teknikleri ile yapı malzemelerine dönüşümünün sağlanması, ekonomik, sosyal ve çevre açısından oldukça önemli kazanımlar getirecektir.

Portland çimentosunun zararlı etkileri göz önünde bulundurulduğunda, son yıllarda alüminosilikat bazlı malzemelerin alkali aktivasyon ile yapı malzemeleri üretilmesi konusuna olan ilgi artmıştır. Bu bağlamda ön plana çıkan en önemli malzeme sınıfı jeopolimer olarak adlandırılmaktadır. Jeopolimerler belli bir alüminosilikat içeriğine sahip atık malzemelerin, alkali hidroksit ve alkali silikat gibi kimyasal aktivatörler ile reaksiyonu sonucu üretilen ve Portland çimentolu betonlara göre yapısal ve çevresel anlamda oldukça avantajları olan malzemelerdir. Literatürde çeşitli fabrika ve tesislerin üretim sürecinde atık malzeme olarak ortaya çıkan uçucu kül, silis dumanı ve yüksek fırın cürufu gibi malzemeler ile jeopolimer geliştirilmesine ilişkin birçok çalışma bulunmaktadır. Bu tür atık malzemelerin giderek artmasının sonucunda hem doğaya ve çevreye verdiği zararların önüne geçebilmek, hem de alternatif yapı malzemesi geliştirilmesinde kullanılarak Portland çimentosu üretimini minimuma indirmek için jeopolimer çalışmaları büyük önem taşımaktadır.

Bu çalışma son yıllarda giderek artan, inşaat ve yıkıntı atıklarının kullanılmasıyla Portland çimentolu betonlara alternatif olmak üzere jeopolimer malzeme geliştirilmesini hedeflemektedir. Araştırma kapsamında amaç ilk olarak inşaat ve yıkıntı atıkları ile jeopolimer bağlayıcılar geliştirmek, ardından Portland çimentolu betonlar ile kıyaslanabilir düzeyde jeopolimer beton üretmektir. Çalışmanın devamında, donatılı jeopolimer kiriş ve donatılı Portland çimentolu kiriş üretilerek dört noktalı eğilme testleri sonucunda yük-deplasman, moment-eğrilik sonuçlarını kıyaslamak amaçlanmıştır. Elde edilen sonuçlar, jeopolimer kirişlerin Portland çimentolu kirişlere göre benzer performans sergilediğini göstermiştir. Bu çalışma sonucunda Portland çimentosunun zararlı etkilerini azaltmaya yönelik çevre dostu ve sürdürülebilir jeopolimer yapı elemanları geliştirme konusunda önemli çıktılara ulaşılmıştır.

Anahtar Kelimeler: Jeopolimer Kirişler, İnşaat ve Yıkıntı Atıkları, Kesme Testleri, Beton Kirişler, Sürdürülebilir İnşaat

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SYMBOLS AND ABBREVIATIONS

Abbreviations

CDW	Construction and Demolition waste
a/d	Shear Span to Effective Depth Ratio
GBFS	Ground Granulated Blast Furnace Slag
FA	Fly ash
HB	Hollow Brick
RCB	Red Clay Brick
RT	Roof Tile
GW	Glass Waste
CW	Concrete Waste
LVDT	Linear Variable Differential Transformer
NaOH	Sodium Hydroxide
Na ₂ SiO ₃	Sodium Silicate
Ca(OH) ₂	Calcium Hydroxide
SEM	Scanning Electron Microscopy
XRD	X-ray Diffraction Analysis
XRF	X-ray Fluorescence Analysis

1. INTRODUCTION

1.1. General

Portland cement is one of the most used man-made materials around the world. Increasing population and related urbanization gradually increase the need for structures and infrastructures, of which Portland cement constitutes the main component. This inevitably leads to a growing trend in the consumption of Portland cement. However, it is known that Portland cement production is responsible for large amounts of energy consumption and high amount of carbon dioxide (CO₂) emissions. As a result of one-ton cement production, approximately 0.94-ton CO₂ is released (Gartner, 2004), and the cement industry is responsible for approximately 5-8% of the CO₂ released into the atmosphere worldwide (Scrivener and Kirkpatrick, 2008). Furthermore, the manufacture of cement consumes a considerable amount of natural resources. To mitigate these side effects of cement, the cement content of the buildings must be reduced by replacing it with other ingredients, such as slag, fly ash, rice ash, etc.

In the past few decades, various aluminosilicate-based precursor materials, including by-products and industrial waste, have been investigated as alternative binders to minimize these harmful effects of cement. The environmental impact of building materials produced by the use of such waste materials, called "green concrete", is very low compared to cement systems (Obla, 2009). Studies on alkali-activated material development as a result of its reaction with alkalines such as sodium hydroxide, sodium silicate, calcium hydroxide, etc. have become widespread in recent years. Alkali-activated materials and geopolymers are one of the most prominent material classes within the scope of green concrete. When the optimum mixture designs are made with a good examination of the material properties, it could exhibit mechanical properties comparable to conventional Portland cement systems. In addition to the significant mechanical advantages of geopolymers, one of the most important features is that they offer environmental advantages over traditional cementitious systems.

Another issue to be considered in the construction sector is the construction and demolition wastes (CDW), which have been increasing gradually for years. Due to disasters such as earthquakes, maintenance/repair operations, demolitions in the construction sector worldwide, the generation of CDW-based concrete, wall elements, glass is becoming uncontrollable day by day. Environmental damage and storage space occupation by increasing CDW have become a growing concern. Failure of the structures to meet the expected functionality causes problems such as high traffic density, fuel consumption, gas emission, by bringing the continuous maintenance, repair and/or renewal processes of the damaged structural elements during their service life. In addition, these repeatedly applied processes may not be long-lasting, which may lead to consequences such as the complete demolition and reconstruction of the structures.

For this reason, studies on recycling these materials have been of particular interest all over the world. Intensive research has been carried out on recycling these materials, which have chemical content suitable for geopolymerization, into building materials as a result of alkali activation. If this goal is achieved, both the harmful effects of CDW, whose amount is increasing day by day, will be minimized and alternative environmentally friendly building materials to Portland cement, which is known to be harmful to the environment, will be developed.

In the literature, while traditional Portland cement systems are produced and analyzed on a large scale in structural dimensions, the study of the geopolymer structural component is quite restricted. Geopolymers produced as an alternative to cement. In this sense, analyzing geopolymer elements and integrating them into the construction practice in the fastest way will allow to reach the goal of sustainable and environmentally friendly structures.

1.2. Research Objectives and Scope

Within the framework of the research plan, it is aimed to provide the benefit by developing high-performance new building materials produced from the CDW. Making the CDW usable through basic and simple processes such as sorting, crushing and grinding without requiring any pre-treatment in the production of building materials gives a unique value to the evaluation of CDW and to produce new generation building materials with high

performance. The primary purpose of this dissertation is to produce and analyze environmentally friendly green geopolymer beams that can exhibit sufficient mechanical properties.

The first step of the study consists of determining the compressive strength to measure the binding capacity of CDWs by recycling roof tiles, hollow bricks, red clay bricks, glass and concrete wastes, which constitute an important part of the CDW. Determining the mechanical properties of the CDWs in this way will be an important finding in order to optimally design the mixture required to produce geopolymer beams.

After the development of the geopolymer binder, the study was continued with the development of geopolymer and concrete mixtures and the determination of their mechanical properties by including the graded fine and coarse aggregates in the system, and the highest performance geopolymer mixtures were selected for the development of geopolymer beams. After this section, it was aimed to design traditional Portland cement concrete mixtures in order to compare geopolymer beams with concrete beams in structural terms. Thus, it is targeted to determine the usability of geopolymers in the construction sector by making structural comparisons due to production of beam samples with geopolymer and concrete mixtures that exhibit similar performance in terms of mechanical properties.

In the final stage of the study, geopolymer and concrete mixtures with similar mechanical performance are produced. In this context, shear-critical beam samples were produced. Three different a / d ratios (0.49, 1.00 and 1.65) were used for shear-critical beams to examine different failure modes in the experiments. Load-displacement performance and moment-curvature performance graphs of beam specimens produced within the scope of the study were examined and additionally, their properties such as yield load and yield displacement and stiffness were compared.

2. LITERATURE REVIEW

2.1. Geopolymer Binders

Geopolymers or alkali-activated binders are materials obtained by reacting a highly aluminosilicate source material with an alkaline solution. In the 1970s, Joseph Davidovits firstly used the term geopolymer to describe the form of substance created by the reaction of aluminosilicate precursor with the alkaline activators (Davidovits, 1982a). Geopolymers involve silico-aluminates consisting of Si^{4+} and Al^{3+} bonds with oxygen. The materials usually are ring polymers and basic chain, and their structure can be semicrystalline to amorphous. The polymerization consists of chemical reactions under alkaline conditions in aluminosilicate based materials that produce polymeric SiO-AlO bonds, with the formulation of; $\text{Mn-SiO}_2\text{-AlO}_2\text{n}\cdot\text{wH}_2\text{O}$ where M is an alkali cation, n is the polymerization degree, and w is the water molarity (Davidovits, 1991).

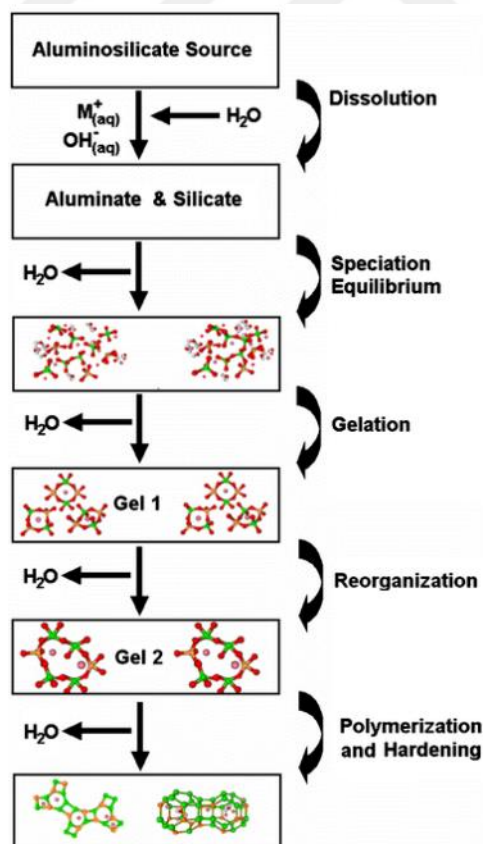


Figure 2.1. Geopolymerization process (adapted from Davidovits, 1994)

Geopolymers developed primarily as a fire-resistant material class. After a short period of time, research and development studies on geopolymers started to expand worldwide due to their technical advantages such as high early strength gain, chemical and dimensional stability, and low permeability. Thus, the production and development of geopolymer materials shifted to the construction industry. According to Wastiels et al., (1993) findings, various aluminosilicate-based industrial wastes and by-products have started to be used in the production of geopolymers with high mechanical and durability properties as a result of alkaline activation.

As it is known, geopolymers, which emerged as a fire-resistant material class for the first time, have had superior properties that can be used as building materials with continuous development in the following periods. In addition to its high mechanical and durability properties, its environmental advantages have also been another feature that cannot be ignored. In this context, as a result of research and analysis, it has been reported that geopolymers have 9% less CO₂ footprint than conventional Portland cement systems (Turner and Collins, 2013). However, this varies widely with the alkali activators used in developing geopolymers. It has been reported in the literature that sodium hydroxide, one of the most commonly used alkali activators in the production of geopolymers, causes 1.915 kg of CO₂ release per kg (Duxson et al., 2007). In addition, it has been reported that sodium silicate, another alkali activator, causes 1.514 kg of CO₂ release per kg in the production (Duxson et al., 2007). Although these numbers are thought to be high, geopolymers are highly advantageous compared to cementitious systems in terms of CO₂ release due to the fact that the precursor materials constituting the main binding part of the geopolymer are waste and alkali activators are used at very low levels compared to the total weight of the mixture.

Various construction applications were carried out using metakaolin within the scope of the development of geopolymer and alkali activated materials. Considering the chemistry of geopolymer and alkali-activated materials, it is known that the simplest and most straightforward precursor material is metakaolin. Alkaline activation of metakaolin to produce zeolite forms is earlier than enhancing of the geopolymer mechanism (Barrer and Mainwaring, 1972a). However, the high energy requirement for the calcination process and the expensiveness of production of high amount metakaolin limited these activities. The findings and models obtained as a result of alkali activation of metakaolin have also been an insight for geopolymer systems that can be developed with new precursor materials. Later,

in 1993, the first paper was published on alkali-activated binder materials using fly ash released as an industrial by-product (Wastiels et al., 1994). Since those years, research into fly ash-based geopolymers has increased significantly due to their environmental benefits. In particular, many studies have emphasized that geopolymers obtained from fly ash have much lower CO₂ emissions than cementitious binders (Duxson et al., 2007).

Fly ash has been divided into two different categories in the literature as Class F with low Ca content and high alumina and silica content and Class C with high Ca and low ignition loss. Figure 2.2 shows the chemical contents of different classes of fly ash used in the literature and the compressive strength classes of the geopolymers produced with these precursors. Considering the ternary diagram of chemical composition and compressive strength classes, it is clearly seen that the chemical composition has a significant impact on the mechanical performance of geopolymer binders.

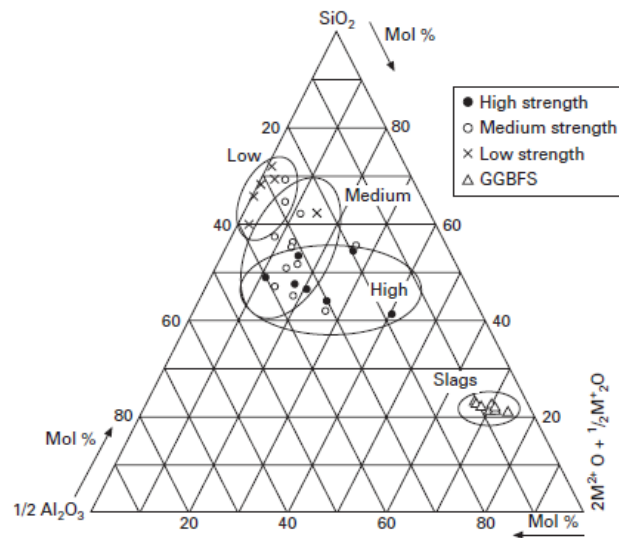


Figure 2.2. Three-fold diagram of fly ash and slag (adapted from Provis and van Deventer, 2009)

Ground blast furnace slag is another precursor material used in the production of geopolymer and alkali-activated systems. Depending on chemical content and particle size, blast furnace slag can show hydraulic binding properties like Portland cement. However, since it is not as reactive as Portland cement due to its nature, it takes a long time to gain binding property. For this reason, it is proven in the literature that it can achieve a high degree of a binding property when it is activated with alkaline activators instead of water, or when it is

substituted into Portland cement in some proportions (Wang et al., 1995). Additionally, in the geopolymerization reactions of the blast furnace slag, CASH gel formation begins early in the reaction. It is thought that the amount of alkali required in the formation process of this type of gel is higher than the gels formed after the Portland cement hydration. It was found that the amount of Ca supplied to the system slows down the reaction processes (Hong and Glasser, 1999).

Jimenez and Puertas (2003) investigated the strength and hydration behavior of slag with alkali activator combination in their study. The authors designed three different activator combinations: sodium carbonate, sodium silicate, sodium hydroxide and, with the Na₂O content being 4% of the binder ratio. According to their results, they observed that the dissolution rate of the slag was highly dependent on the pH of the environment, and they reported that pH greater than 12 had a positive effect. The authors observed that in cases where pH is greater than 12, setting time and compressive strength are determined mainly by the anions coming from the activator, and these anions react with Ca ions released by the dissolution of the slag to form stable hydration products.

Wang et al. (1993) examined the parameters affecting the strength of alkali active slags in their study. According to the findings of the authors within the scope of the study, parameters such as liquid/slag ratio, silicate module, activator type and combination, curing conditions were the most critical parameters in determining the strength properties of alkali-activated slag. The authors concluded that under all conditions, sodium silicate is the best performing activator, the optimum Na₂O ratio is 3.0-5.5%, the optimum solution/slag ratio is 0.38-0.45, the optimum slag fineness is average 4750 cm²/g.

Gruskovnjak et al. (2006) studied on the alkali-activated slag and compared it with conventional Portland cement systems. The authors have characterized the hydration products of slag and cement by various microstructural analyzes such as scanning electron microscope and X-ray diffraction. According to their findings, they reported that the hydration kinetics of slag and cement are quite different, the formation of C-S-H after hydration of slag occurs very rapidly compared to cement systems, and this is related to the rapid dissolution of Na-metasilicate in alkali-activated systems. It has been observed that the kinetics of the slag has changed as a result of its rapid consumption during the ongoing hydration of the slag, and it has gained a slower late strength compared to cement systems.

Many studies have been carried out by combining the precursors used in geopolymer and alkali-activated systems together in the literature. Features such as the partially self-binding property of blast furnace slag, the ability to increase the mobility of water in the system due to the spherical particle structure of fly ash, the ability to increase the workability, the fine particle size of silica fume and the high SiO₂ content can be combined to develop geopolymer systems with optimum mechanical and durability properties. Bernal et al. (2010) examined the effect of metakaolin substitution on the systems containing alkali-activated slag. Researchers reported that the carbonation was accelerated further by the substitution of metakaolin and observed that calcite was the primary carbonation product. In addition, they stated that the gel formation mechanism and the resulting strength development in systems with metakaolin substitution was high, thus reducing the carbonation rate.

Alonso and Palomo (2000) investigated the activation mechanism of metakaolin and calcium hydroxide mixtures and the effect of activator molarity, solid ratio, and curing conditions. The authors reported that sodium hydroxide higher than 10M did not yield a considerable change in the presence of calcium hydroxide within the gel formed in metakaolin activation. In addition, it has been reported that the increase in the metakaolin/calcium hydroxide ratio increases the hydration temperature and provides more gel formation.

Dombrowski et al. (2006) examined the fly ash-based geopolymers. They examined the structural properties, setting time and gel mechanism of the mixtures by adding calcium hydroxide in various proportions. According to their results, the authors stated that the increase in calcium content enhanced the reaction degree and caused better mechanical performance, and that the mixture with the best performance contained 8% calcium hydroxide. They also noted that the addition of 8% calcium hydroxide performed well in both ambient conditions and high curing temperatures.

Buchwald et al. (2007) discussed the effect of various combination of metakaolin and slag-based mixtures on the mechanical performance and structural properties of the final product. When the authors examined the gel structure of the final product, they reported the co-existence of the C-S-H gel formed after slag activation and the aluminosilicate gel formed as a result of metakaolin activation and noted that high mechanical properties were achieved with the high rate of formation of both gels.

Li and Liu (2007) examined the effect of slag addition on fly ash-based geopolymers on compressive strength. The authors designed two different mixtures with 0% and 4% slag content and applied two different curing temperatures of 30 °C and 70 °C to the samples. According to their findings, they observed that 4% slag addition had a positive effect up to 70 MPa compressive strength values. The authors explained this situation by the increased reaction rate and the increased gel formation in the matrix due to the addition of slag. In addition, they reported that with the addition of slag, the pore structure of the geopolymers was improved, which occurred especially in curing conditions at 70 °C.

Najini et al. (2018) investigated alkali-activated materials with natural pozzolan and slag combination in order to examine precursor material. The authors also investigated the impact of the precursor material combination as well as the effect of alkali activator type and combinations on mechanical properties. According to their results, the authors stated that the kinetics of alkali-activated materials differ considerably compared to Portland cement systems. They reported that fluidity properties decreased with the reduction in the amount of natural pozzolan. In addition, they noted that the fluidity showed an improvement with the increase in sodium hydroxide molarity. Considering the compressive strength results, they stated that the use of sodium silicate as an activator had a positive effect. They also reported that the improvement in compressive strength accelerated with the slag increment in the mixtures. The authors have observed that the alkali-activated material had higher performance compared to Portland cement systems, especially in terms of chloride penetration. In addition, they reported that the depth of chloride penetration decreased with the use of natural pozzolan.

Fernandez et al. (2008) examined the alkali activation properties of metakaolin and calcium aluminate mixture in their study. They activated their mixes with 8M sodium hydroxide and, after casting, subjected samples to a thermocycle of 85 °C for 2 to 20 hours. The authors reported that after mechanical and microstructural analyzes, calcium aluminate cement could be used as a reactive aluminum source. As a result of microstructural analysis, the gel structure formed due to alkali reactions of metakaolin and calcium aluminate cement is N/C-A-S-H.

2.2. Alkali Activators

Besides the nature of the precursor material, the type and ratio of the alkali activator are of great importance for geopolymer production. In the literature, alkali hydroxide and alkali silicate group activators are generally used to activate aluminosilicate precursors. In both types of activator groups, sodium and potassium stand typically out as alkalis and show the best performance. The high solubility of sodium and potassium hydroxides up to 20 moles provides quite flexibility in geopolymer production (Kurt and Bittner, 2006). Availability of alkalinity is higher for alkali silicates at similar pH values than alkali hydroxides. Although alkali hydroxides provide high pH in the early reaction period, a more pH level is reached in the future due to the silica provided by the alkali silicates to the system (Provis and van Deventer, 2013).

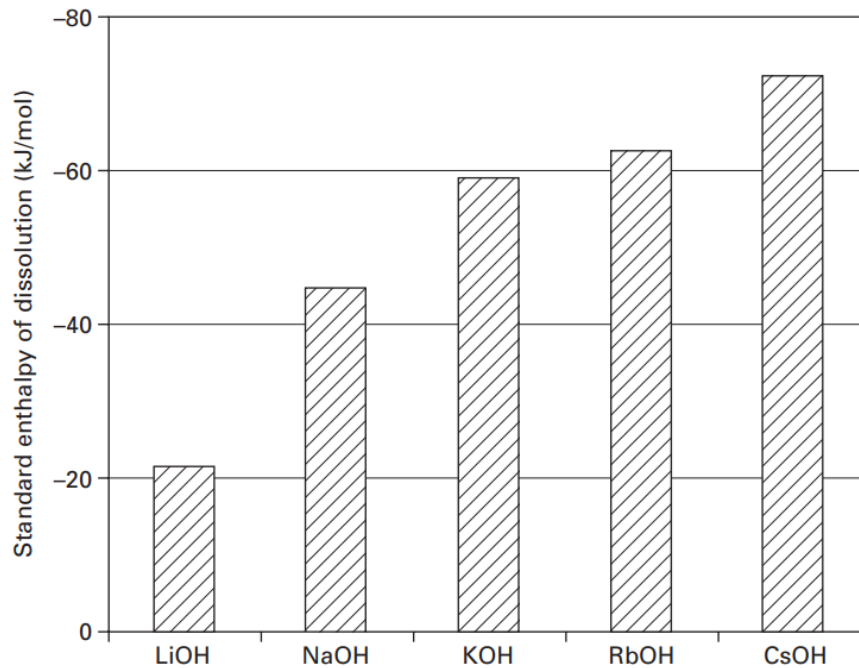


Figure 2.3. Dissolution properties of alkali hydroxides (adapted from Gurvich et al., 1996)

Tanakorn et al. (2016) examined the effect of sodium silicate and hydroxide on the geopolymers. They designed a series of mix designs including 60 grams of sodium hydroxide, 20 grams of sodium hydroxide and 40 grams of sodium silicate, and 60 grams of sodium silicate. When they examined the strength results, they reported that the combination of both activators gave the highest strength result. In contrast, the mixtures where sodium hydroxide was used alone showed the lowest strength result. In addition, the authors

emphasized that the $\text{SiO}_2 / \text{Al}_2\text{O}_3$ and $\text{CaO} / \text{SiO}_2$ ratio is a critical parameter in controlling the compressive strength of the samples and they also reported that the highest performance was achieved when the $\text{SiO}_2 / \text{Al}_2\text{O}_3$ ratio was in the 3.4-3.6 range and the $\text{CaO} / \text{SiO}_2$ ratio was in the 0.72-0.80 range.

Risdanareni et al. (2014) studied various activator types and molarities of mixtures containing fly ash of the geopolymer. The authors designed a mixture with two different sodium hydroxide molarities, 8M and 10M, and five different ratios of sodium silicate and sodium hydroxide, 0.5, 1.0, 1.5, 2.0, and 2.5, within these molarities. At the end of the study, the authors reported that the increase in sodium hydroxide molarity generally beneficial on the mechanical properties of geopolymers, and stated that future studies were required to find the optimum ratio. In addition, the authors concluded that the maximum performance was achieved when the activator ratio was 2 in mixtures containing 8M sodium hydroxide and the activator ratio was 2.5 in mixtures containing 10M sodium hydroxide. As a result of the study, the authors proved that geopolymer with structural features could be developed with the alkali activator design in appropriate ratios with a 30.97 MPa.

Chindaprasirt et al. (2006) analyzed the effect of various sodium hydroxide molarity and sodium silicate ratios on the compressive strength and workability of high calcium fly ash-based geopolymers. They designed various mixtures such that activator ratio is 0.67, 1, 1.5, and 3, and sodium hydroxide molarities are 10, 15, and 20. According to their results, they reported that the increase in sodium hydroxide and sodium silicate concentrations caused a decrease in the flowability of mortars. Therefore, they claimed that the reduced workability could be improved by using extra water or superplasticizer. When examining the effect of alkali activator on compressive strength, they observed that the sodium silicate/sodium hydroxide ratio exhibited optimum values between 0.65-1. There was no significant effect between 10M and 20M in terms of sodium hydroxide molarity.

Deb et al. (2014) examined the effect of sodium silicate and sodium hydroxide use on compressive strength and workability properties by curing fly ash and slag based geopolymers in ambient curing. In this context, the authors determined the alkali ratio as 35% and 40% and chose the activator ratio between 1.5-2.5. Similar to some findings in the literature, the authors observed that the decrease in alkali concentration had a negative effect on workability. At the same time, they stated that the inclusion of extra water could be

considered in improving workability. The authors obtained the maximum compressive strength as 51 MPa using a 40% activator and 1.5 sodium hydroxide/sodium silicate ratio.

Vladimir Zivica (2006) studied on the alkali activator type and molarity on the rheological characteristic of alkali-activated slag. According to the results of the study, the author reported that sodium carbonate, sodium silicate and sodium hydroxide accelerated the setting time and decreased workability at 7%, 3% and 5% concentrations. In addition, the author reported that the use of sodium silicate caused an incredible reduction in setting time and could cause restrictions in structural applications when no retarding additives were used. As a result, the author stated that by making the alkali activator combination correctly, alkali-activated materials with optimum properties could be produced.

Ravikumar and Neithalath (2012) investigated the effect of Na₂O and Na₂O / SiO₂ ratios depending on alkali concentrations on reaction products of alkali-activated slag. The authors observed that high alkali dosages (high Na₂O values) in the mixtures they produced with the combination of powder sodium silicate and sodium hydroxide showed high-temperature peaks and had a positive effect on both early and late compressive strength. While C-S-H gel formation with a low Ca / Si ratio was observed in mixtures with low alkali concentrations, it was reported that extra silicate gel formation was observed in mixtures with high alkali concentrations.

The most crucial finding obtained in the literature studies within the scope of the effect of alkali activators on alkali-activated systems and geopolymers is that although the type and concentration of alkali activator has important on the properties of the final product, the type and properties of the precursor material used also have an important effect. Properties such as silicon, aluminum and calcium oxide ratios, particle size, reactivity, bond type, and structure of the precursor material used in this context are the most important criteria for choosing the appropriate activator type and dosage. While sodium hydroxide and sodium silicate come to the fore in the selection of alkali activators based on these properties, activators such as sodium carbonate and potassium hydroxide have also been used in some limited studies, but no significant results have been obtained. One of the essential findings observed in the literature is that geopolymer materials with high compressive strength and durability properties can be produced by optimizing ratios such as the appropriate activator

type and combination, concentration, silicate module according to the properties of the precursor materials.

2.3. Construction and Demolition Waste-based Geopolymers

Recently, the use of CDW in geopolymerization has come in view as a topic of interest to researchers around the world. The alumina and silica composition of CDW, makes it possible to recycle these materials in the building industry. Although various CDWs have been successfully used in geopolymer topic in the literature recently, the obtained performances differed. In this section, previous research and development studies on CDW based geopolymers are fundamentally mentioned.



Figure 2.4. The process from CDW-based precursor to CDW-based concrete (adapater from Robayo-Salazar et al., 2020)

Geopolymerisation technology, which has been successfully used with industrial wastes such as fly ash and slag recently, is recognized as an essential option for the reuse of inorganic material found in construction demolition wastes. Puertas et al. (2006) studied alkali-activated ceramic wastes in a mixture containing 6M NaOH and Na₂SiO₃ and found a 13 MPa. The researchers attribute these results to the semi-crystalline nature of such materials. Khater (2012) activated waste concrete, cement-based waste materials and slaked lime with sodium hydroxide and sodium silicate in a study. As a result of the study, he

obtained compressive strengths between 3-55 MPa in geopolymer paste samples and reported that the $\text{SiO}_2 / \text{Al}_2\text{O}_3$ ratio between 3.0-3.8 had great impact of the performance.

Allahverdi and Hani (2013) combined concrete waste and brick waste in their study. They activated it by using Na_2O with 8% of the binder amount and Na_2SiO_3 with a silica module 1.4, and at the end of the study, they reached 50 MPa.

Vásquez et al. (2016) conducted a study with Portland cement, concrete waste, and metakaolin mixtures and obtained a result between 3-55 MPa compressive strengths. They emphasized that the percentage of alkali activator is very important. The addition of metakaolin and portland cement provides better dissolution of the crystal phases in concrete wastes and improves mechanical properties.

Efforts to produce building materials by recycled CDWs by geopolymerization have gained significant momentum in recent years. Mahmoodi et al. (2020) developed a high-performance geopolymer binder exceeding 80 MPa after 28 days of ambient curing with concrete waste and blast furnace slag. Similarly, Ulugöl et al. (2021) developed a geopolymer binder that exceeds 45 MPa in oven curing using CDW-based masonry and glass. On the other hand, Yıldırım et al. (2021) combined CDW-based precursor materials binary and activated them with sodium hydroxide and reached a compressive strength result of 80 MPa after 48 hours of curing at 115 °C.

In another study, Robayo-Salazar et al. (2020) activated CDW-based waste materials using sodium hydroxide and sodium silicate and subjected the samples to ambient curing. As a result of the study, they have reached a high compressive strength up to 43.9 MPa in 90 days of ambient curing. Studies have proved that CDW-based waste materials can be successfully recycled, and high-performance and eco-friendly building materials can be developed as an alternative to Portland cement.

Rossi et al. (2019) conducted a study on the fresh and hardened characteristics of particle size change of construction and demolition waste in fly ash-based geopolymers. The authors used sodium hydroxide and sodium silicate as alkali activators in their studies, while they used fine construction and demolition-based materials as aggregates. According to their results, they found the compressive and flexural strengths of geopolymers based on

construction and demolition waste to be 40 MPa and 8.5 MPa, respectively. In addition, compressive and flexural strengths of sand-based geopolymers were 23 MPa and 3.1 MPa, respectively. Additionally, they reported that the geopolymers oriented from CDW have low fluidity, and this is by the reason of the high water absorption property of the mortar residue in the concrete waste.

Zaharaki et al. (2016) studied the alkali activation of geopolymers combined with industrial waste and CDW. While the authors used various proportions of sodium hydroxide and sodium silicate in their studies, they first subjected heat curing the samples at 80 ° C for 24 hours and then store them in ambient conditions for seven days. According to their results, they reported that increasing sodium hydroxide from 8M to 10M had a positive effect. In addition, they claimed that building materials with satisfactory properties could be produced by successfully activating construction and demolition waste and red mug and slag. When the properties of the final product were examined, they noted that the $\text{SiO}_2 / \text{Al}_2\text{O}_3$ and $\text{SiO}_2 / \text{CaO}$ ratios had a significant effect.

2.4. Reinforced Geopolymer Concretes

Studies on geopolymer in the literature have generally been carried out on the mechanical characteristics such as compressive strength and microstructural characterization of the final product. However, although these geopolymer products have been successfully developed in terms of both mechanical and durability, structural element tests are also required for large-scale applications. In light of all these concerns, research on reinforced geopolymer concretes has been gaining momentum in recent years. It is imperative to produce structural elements with reinforced geopolymer concretes and to examine the structural analysis and modeling of these elements. Additionally, the compatibility of the design criteria of traditional Portland cement systems standardized in building and earthquake regulations with beams and columns produced with reinforced geopolymer concretes is an issue that needs to be investigated.



Figure 2.5. First public structure built with structural Geopolymer Concrete: The University of Queensland, Australia, 2014

Although limited, there are comprehensive research and findings in the literature about reinforced geopolymer concretes. Sumajouw et al. (2005) examined the behavior of fly-ash-based reinforced geopolymer beams and compared the results with those of conventional cemented concrete. The authors found the compressive strength between 34 MPa and 46 MPa and the failure load value between 112.6 kN and 326.00 kN. They reported that the reinforced geopolymer beams showed similar behavior and strength performance compared to traditional cementitious beams.

PU Kumar and BSC Kumar (2016) produced geopolymer beams based on blast furnace slag and metakaolin and examined their flexural behavior and compared them with that of cementitious beams. According to their results, the authors reported that the geopolymer and Portland cement beams exhibit almost the same behavior in terms of load-deflection characteristics and the crack patterns. Still the crack moment is lower than Portland cement systems.

Jeyasehar et al. (2013) developed fly ash-based geopolymer precast elements and tested the suitability of geopolymers for structural applications. They produced geopolymer beams with solution / fly ash ratios ranging from 0.4 to 0.55 and conventional cemented beams as a reference. According to their results, they reported that geopolymer beams were better than

cemented beams in terms of initial crack load, yield strength, ultimate load and average crack width.

In a study conducted by Kumaravel and Thirugnanasambandam (2013), the flexural property of a low Ca fly ash-based reinforced geopolymer beam was investigated. The authors compared the beam properties of geopolymer concrete and cement concrete with similar compressive strengths. They showed that geopolymer concretes were 7.9% better than cemented concrete in terms of service load. Similarly, they reported that the geopolymer beam is 5.68% stronger than the cement beam in terms of average ultimate load-carrying capacity.

2.5. Structural Tests of Reinforced Geopolymer Concretes

It is crucial to use environmentally friendly and green geopolymer materials developed as an alternative to Portland cement on a structural scale. Although it is a priority to test and define the compressive strength and durability properties of the developed building material initially, tests of the structural elements produced with these materials are also needed. In this context, it is one of the most essential requirements to measure the resistance of structural elements such as columns, beams, curtain walls, slabs to the loads they will encounter during their service life by structurally analyzing and characterizing them. In this way, determining the bearing capacities of these elements and their behavior against lateral and vertical loads and making the appropriate reinforcement process will allow for longer-lasting, and reliable construction applications.

One of the most important criteria determining the structural performance of reinforced geopolymer concrete elements is the properties of the bond between geopolymer and reinforcement. The strength of the bond directly affects many properties such as the bearing capacity of geopolymer building elements, crack width, and pattern. Although the relationship between bond strength and such properties has been standardized for traditional Portland cement structural systems, new standards and characterizations can be required for geopolymer-based structural elements, as the mechanism of geopolymers, matrix chemistry, and adherence properties between reinforcement are quite different. For these reasons, there are quite several studies in the literature examining bond strength for structural geopolymers. In the next parts, a detailed literature summary of the structural tests applied within the scope

of reviewing many parameters such as bond strength, bearing capacity, bending and deformation characteristics of structural elements designed with reinforced geopolymer concrete and the findings obtained as a result of these tests are presented.

2.5.1. Geopolymer Beam Tests

There are various studies in the literature on the development of reinforced geopolymer concrete as a structural dimension beam element and testing it with various methods and analyzes. Sofi et al. (2007) investigated their bond strength performance by producing fly ash-based inorganic polymer concretes and cube and beam elements. According to their findings, it was observed that all of the beam elements resulted in splitting type failure due to fragmentation of the binding material surrounding the reinforcement. According to the test methods they compared, they concluded that the bond performance of the beam end specimens was lower than the pullout tests and reported that the direct pullout test might be more suitable for measuring bond strength.

In their study, Aslam and Khadiranaikar (2016) examined the flexural behavior of geopolymer beams with blast furnace slag and fly ash mixed with 1200 mm effective span. They characterized the behavior of geopolymer beams based on parameters such as load-deflection behavior, initial crack load, ultimate load, and compared the results with conventional cemented beams. According to the test results, the geopolymer beams showed a ductile failure in flexural mode due to crushing in the compression zone. They found that the bending capacity of geopolymer beams is highly affected by the tensile reinforcement ratio and the compressive strength of the geopolymer binder from which they are produced. Additionally, it was seen that the crack load and moment increase with the compressive strength, and the increase in the ratio of longitudinal tensile reinforcement has a similar effect. The authors confirmed that the values obtained as a result of the geopolymer beam tests showed properties similar to traditional Portland cement beams and could be used in structural dimensions.

Visintin et al. (2017) examined the shear behavior of geopolymer beams without stirrup in a study where they used F class fly ash as a binder and activated fly ash. They measured the shear behavior of geopolymer beams with four direct shear tests and compared the results with the segmental approach. The authors concluded that shear results and friction-shear

properties are among the properties of conventional Portland cement concrete, but that further research and modeling is required. At the same time, they reported that the approach they applied was very successful in determining failure load and that relatively new building materials such as geopolymer would offer significant advantages in determining these properties.

Yost et al. (2012) produced beams with alkali-activated fly ash concretes and investigated the properties of beams such as over-reinforced, under-reinforced and critical shear with a four-point bending test and compared the geopolymer beams with traditional Portland cement beams. The authors found that the load-induced crack formation is the same in geopolymer beams and cementitious beams. Besides, they noted that the elastic behavior and failure mode of under-reinforced geopolymer beams and cementitious beams were similar. In over-reinforced cases, they observed that the load-displacement curves of the geopolymer beams were linear, while the load-displacement curves of the cemented beams were slightly non-linear. They reported that geopolymer beams exhibit highly brittle behavior compared to cement beams in flexural tests. As a result, the authors noted that geopolymer beams behave quite similarly to cemented beams compared to the test methods applied by four-point bending test results, according to similar compressive strength and aggregate ratio.

Darmawan et al. (2019) evaluated the shear strength of geopolymer beams containing fly ash in their study. The authors found the compressive strengths of geopolymer concretes in the range of 22-46 MPa, and the splitting-tensile strength of geopolymer concretes in the range of 2.38-3.12. They examined the crack pattern and crack development of the samples, which were subjected to two different curing environments, namely ambient conditions, and seawater curing, at the end of 28 days and reported that the two different curing methods exhibited similar results. However, they reported that the cracking load increased to higher rates in seawater curing. In addition, they found lower porosity and high concrete resistance in samples cured under ambient conditions.

Maranan et al. (2016) examined the shear behavior of geopolymer beams with GFRP bar reinforcement in their study. In the beams they produced with six different reinforcement designs, they first took the a/d ratio as 1.8, and then designed the a/d ratio of the beam with the same cross-sectional area as 4.7 in order to examine the effect of the a/d ratio.

According to their findings, the authors found that the deformation capacity and shear strength were improved by 200% with the use of GFRP bars. In addition, they reported that if the reinforcement ratio increased by 11%, the load-carrying capacity increased by 22%. The authors observed that beams with a ratio of 4.7 a/d had a lower crack stiffness than beams with a ratio of 1.8 a/d. The authors attributed this to the fact that the increased a/d ratio might be due to decreased arch motion. In addition, the authors highlighted that beams produced with a ratio of 4.7 a/d exhibited a lower strain value.

Ambiliy et al. (2011) conducted a study on the shear behavior of reinforced geopolymer beams. The authors used Portland cement to produce a control sample in their work while varying proportions of blast furnace slag and fly ash for geopolymer beams. The authors used the same flexural and shear reinforcement as reinforcement in the mixture designs and designed two different ratios of a/d ratio as 1.5 and 2. According to their findings, the authors observed that the load-deflection curve and peak load values of traditional Portland cemented beams and geopolymer beams were quite similar when the middle span load-deformation curves were compared. In addition, they reported earlier initial crack formation in geopolymer beams with an a/d ratio of 2. According to another result of the authors, it was observed that geopolymer beams were 20% higher in compressive strength than cemented beams, while their ultimate load capacity was 15% higher. However, they noted that geopolymer beams with two different a/d ratios had a similar crack pattern to cementitious beams.

Madheswaran et al. (2015) researched the reinforced geopolymer beams due to monotonic static loading. While the authors designed a Portland cement control sample, they designed 12 geopolymer beams with various a / d ratios. The authors reported that according to the results, geopolymer beams showed slightly more deflection. They also noted that while geopolymer and cement beams have similar maximum curvature values, reinforced geopolymer beams exhibit higher maximum curvature values. By comparing all the results they obtained, they showed that the geopolymer could replace cemented reinforced concrete systems in terms of structural performance.

Umniati et al. (2017) analyzed the flexural performance of fly ash-based geopolymers. They compared the compressive strength, maximum load-carrying capacity, and bending shear strength of the reinforced geopolymer beam and reinforced cementitious beams they

designed with 1.11 and 2.24 a/d ratio. According to the results obtained, the authors reported that geopolymers have 26% higher compressive strength than cementitious systems. In addition, they observed that the flexural performance of geopolymer beams was lower than cementitious beams. Simultaneously, the bending collapse was observed in both a/d ratios due to the stiffer bond structure of geopolymer beams, while bending shear collapse was observed in cement beams.

Abraham et al. (2013) carried out a study on the strength and behavior of fly ash-based geopolymer beams and cementitious beams. The authors tested the beams with two-point monotonic loading and made various studies on characteristics such as ultimate load, initial crack load, loading capacity, moment-curvature. According to the results, they reported that the first crack load and ultimate load of the reinforced geopolymer beams performed better than the cemented beams. They reported that all beams exhibit flexural mode fail behavior, while geopolymer beams have more ductile properties. In addition, they noted that geopolymer beams exhibited smaller spaced and narrow cracks under load. In addition, it has been observed that the energy absorption capacity of geopolymer beams performs better than cement beams.

Tung et al. (2019) examined the flexural behavior of fiber-reinforced geopolymer beams in ambient curing. They added up to 1.5% fiber reinforcement to the geopolymer beams, which they produced using fly ash and blast furnace slag. According to their results, they reported that geopolymer beams showed low crack moment and stiffness due to high drying shrinkage and low elasticity modulus. In addition, the authors who reported that geopolymers were extremely brittle observed that the addition of hooked-end steel fiber was very effective in improving crack resistance.

Junaid et al. (2019), examined the flexural and deformation behavior of fiber-reinforced geopolymer concrete (FRGC), geopolymer concrete (GPC), ordinary Portland concrete (OPCC)- and fiber-reinforced concrete (FRC) in their study. The authors tested 8 beams under the four-point bending test. According to their results, they reported that the load-deformation graph displayed a linear behavior in all beams in non-cracked conditions and that GPC and OPC experienced a sudden drop when the first peak load occurred. However, they observed that FRC and FRGC lost stiffness after peak load. In addition, it was observed

that the beams continued to deform under the same load for a while after peak load since they contain fiber instead of the reinforcement bar.

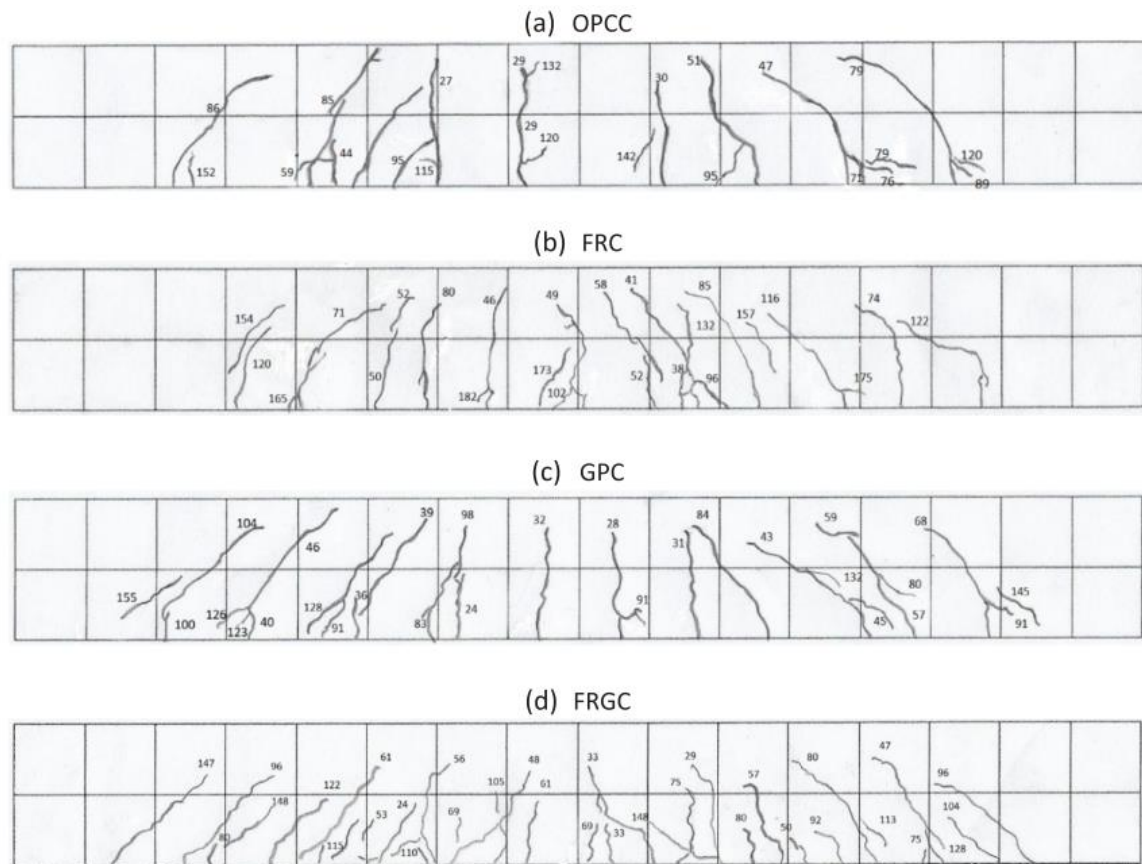


Figure 2.6. Crack patterns of OPCC, FRC, GPC and FRGC beams (adapted from Junaid et al., 2019)

Yacob et al. (2019) examined the shear strength of fly ash-based reinforced geopolymer beams in a study they conducted. While the authors used sodium silicate and sodium hydroxide of various molarities to activate fly ash, they used high range water reducer additives and extra water to overcome workability problems. The authors obtained the compressive strength of the geopolymer cylinders after curing at 65 ° C in 28 days as approximately 40 MPa. The authors produced a sample of cementitious beams for comparison, and they attributed the different crack patterns between cemented beams and geopolymer beams in terms of crack patterns to the shear and shear-flexural crack formation of geopolymer beams under load. In addition, they seen that the a/d ratio, and the reinforcement significantly affected the shear strength. Based on this, they saw that failure

mode changed from shear failure to shear-flexure failure as a result of the increase in the a/d ratio from 2.0 to 2.4.

2.5.2. Geopolymer Joint Tests

Efforts on enhance the ductility performance of reinforced concrete elements have been growing in recent years in order to minimize the losses caused by frequent earthquakes. Since beam and column joints from structural elements are the weakest area in the event of significant loads such as earthquakes, the reinforcement and strength characteristics in this region should be designed in the most appropriate way. In the event of an earthquake, joints are severely damaged due to the cyclic load. For this reason, it is a matter to be considered in terms of design, analyzing these regions with appropriate tests and knowing the load distributions to be transferred to the connecting elements in the whole system. According to the findings obtained from the studies carried out, the structural properties of the beam-column joint are mainly dependent on various parameters such as concrete strength, dimensional properties of beam and column, bond strength, and reinforcement ratio (Haach et al. 2008; Ganesan et al. 2014). Although the fact that the mechanical and durability properties of geopolymers have been investigated frequently until today, studies on the characteristics of the joint areas of geopolymer structural elements have been limited.

In a study by Raj et al. (2016), the properties of beam-column joints under reverse cyclic loading were investigated. The authors tested the energy absorption capacity, energy distribution, ultimate load and initial crack load of the samples they produced. According to their results, they found the performance of the traditional concrete beam-column joint very similar to that of the geopolymer beam-column joint. They noted that in addition to their mechanical performance, the initial crack formation load and energy absorption capacity also had a similar trend.

Yoganand and Kumar (2017), conducted a study on the beam-column joint properties of geopolymer concretes using fiber mats. The authors used fly ash as the geopolymer precursor, and sodium hydroxide and sodium silicate as alkali activators. The authors, who applied Reversal load to the beam-column joints they produced, reached the result of the highest load carrying capacity and energy absorption capacity in the elements using carbon fiber reinforced polymer sheets. However, they stated that the cost of this material was high

and they reported that the use of glass fiber reinforced polymer sheet was the most cost-effective.

In a study, Kumar et al. (2017) conducted a structural analysis of beam-column joints based on geopolymer concrete. According to the experimental results, the authors observed that geopolymer-based beam-column joints showed higher stiffness. In addition, they found that the energy absorption capacity under cyclic loading was 3.17 times higher in geopolymers. The authors emphasized that the geopolymer and conventional concrete they produce had similar costs per cubic meter, while they noted that geopolymer could be a good alternative to conventional concrete in terms of environmental and performance properties.

Datta and Premkumar, (2018) examined the properties of steel fiber reinforced geopolymer beam-column joints. The authors produced four different geopolymer mixture designs based on fly ash and slag, as well as one conventional concrete. The authors tested the samples with semi-cyclic loading and examined properties such as load-deformation, energy dissipation, ductility, and crack characteristics. According to their results, they found the first split load value similar to geopolymer and conventional concrete, and concluded that conventional concrete was more bendable in terms of ductility properties. According to the results they obtained in terms of energy dissipation capacity, they saw that the use of steel fiber in conventional concretes did not cause any change. Among the samples, geopolymers with steel fiber reinforcement exhibited the highest dissipation capacity.

Nath and Lokeshwaran, (2018) investigated the behavior of fiber-reinforced geopolymer beam-column joints under cyclic load. The authors produced two geopolymers and two conventional concrete as part of their work. According to their results, the authors reported that geopolymer beam-column joints performed approximately 11%, 6.5%, 44% and 11% better than conventional concrete beam-column joints in energy dissipation capacity and ductility, respectively. In addition, they noted that fiber reinforcement resulted in a bearing capacity increase of approximately 50% in initial crack formation load for both types of materials.

In their study, Mohanraj and Shahidha (2019) carried out the structural analysis of the reinforced beam-column joints they produced with geopolymer. The authors subjected the cube, cylinder and beam-column joints they produced within the scope of the study to

compression, tensile and bending tests. According to their results, they noted that the geopolymer had performed better than conventional concrete in splitting tensile strength was 24% higher, the compressive strength was 2.16 times higher, the bending strength was 41% higher and the modulus of elasticity was 22% higher.

Saranya et al. (2021) conducted a study on seismic analysis of geopolymer beam-column joints under reverse cyclic loading. While the authors produced geopolymer samples from a mixture of slag and dolomite, they also produced one conventional concrete for comparison. According to their results, they stated that geopolymers showed more ductile properties compared to conventional concretes, and the use of steel fiber provided an improvement of more than 70%. In addition, it was concluded that energy absorption capacity was improved with the use of steel fiber and the curvature ductility value could increase by 150% by using 0.75% fiber. Additionally, a decrease in crack expansion was observed as a result of the use of steel fiber compared to samples of both material types. Hence the use of geopolymer reduces the congestion of reinforcements at the joint area with a better production process.

3. MATERIALS AND METHODOLOGY

The crushing and grinding processes, particle size, chemical analysis and microstructural analysis of the precursor materials used within the scope of the thesis study were presented in this section. In addition, the characteristics and gradation of the natural aggregate and chemical content of alkali activators used in the study were also given in detail. Casting and curing procedures and test methods of mixtures were also presented in this section.

3.1. Materials

In the scope of this study, the precursor materials were hollow brick (HB), red clay brick (RCB), roof tile (RT), concrete waste (CW) and glass waste (GW) which were obtained by CDWs from different regions. In addition to these materials, industrial wastes such as ground blast furnace slag (GBFS) and fly ash (FA) were added to the mixtures at low rates. In the production of geopolymer concrete, natural aggregate was used as aggregate. Sodium hydroxide, calcium hydroxide and sodium silicate are used as alkali activators in the production of geopolymer concrete.

3.1.1. Precursor Materials

CDW materials collected separately from various demolition sites were first broken in a laboratory-type jaw crusher and made ready for further grinding. Subsequently, the precursor materials were individually grinded in the ball mill for one hour. In Figure 3.1, pictures of the CDW-based materials, slag and fly ash are presented before and after each procedure. The particle size analysis obtained after crushing and grinding processes is presented in Figure 3.2.

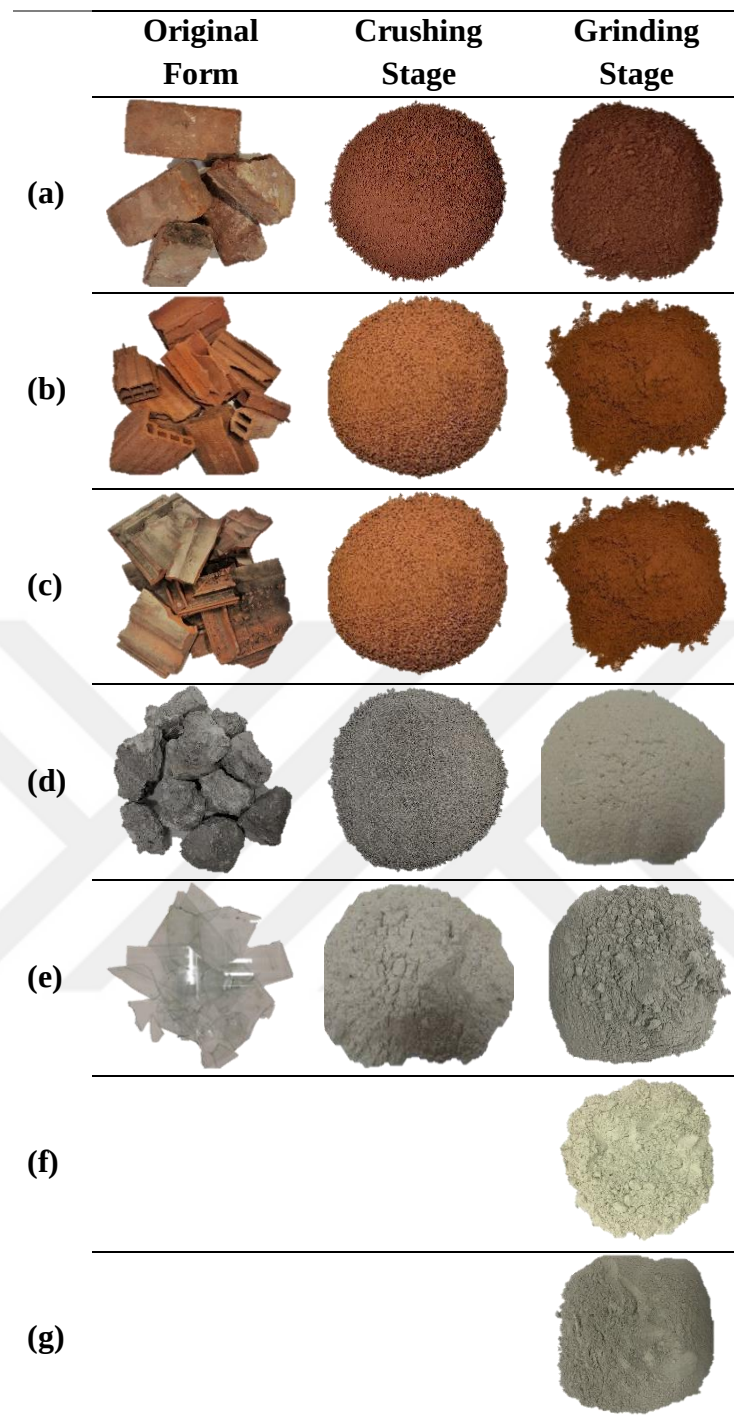


Figure 3.1. Photographs of CDW-based materials: (a) Red Clay Brick, (b) Hollow Brick, (c) Roof Tile, (d) Concrete Waste, (e) Glass Waste, (f) GBFS and (g) FA

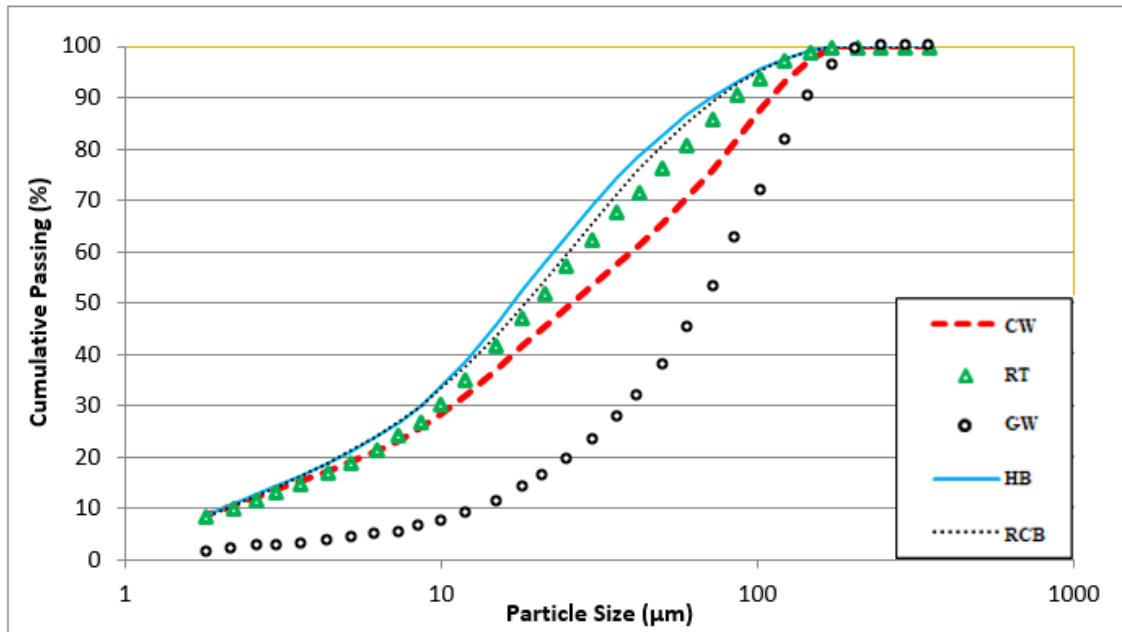


Figure 3.2. Particle size distributions of different CDW materials

When Figure 3.2 is examined after crushing and grinding for one hour, it is seen that the brick-based materials (HB, RCB, RT) have the finest particle size. CW was observed to have a coarser grain size compared to bricks. In addition, GW was the CDW-based material with the coarsest grain size in the study. Since it would not be realistic and practically feasible to make GW thinner and bring it to the brick level, it was not applied within the scope of this thesis study.

Within the scope of the thesis study, it is planned to apply various microstructural characterization to CDW materials. In this context, X-ray fluorescence (XRF) analysis to determine the chemical composition, X-ray diffraction (XRD) technique to analyze the crystalline nature, Scanning electron microscopy and Energy dispersive X-ray spectroscopy (SEM/EDX) analysis to observe morphological and elemental properties were carried out. SEM, XRD and XRF analysis results of the materials are presented in Figure 3.3, Figure 3.4, and Table 3.1, respectively.

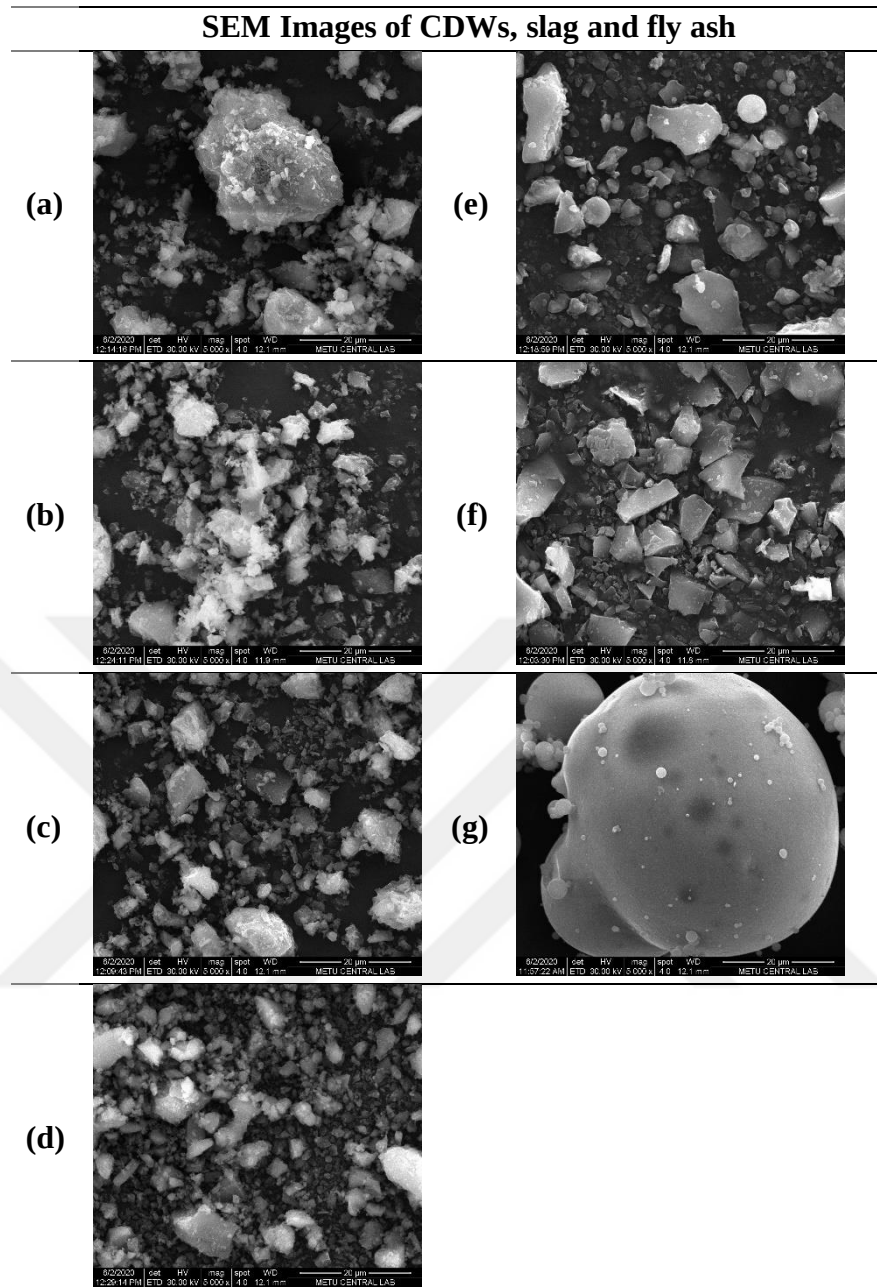


Figure 3.3. SEM Images of CDW-based materials: (a) Red Clay Brick, (b) Hollow Brick, (c) Roof Tile, (d) Concrete Waste, (e) Glass Waste, (f) GBFS and (g) FA

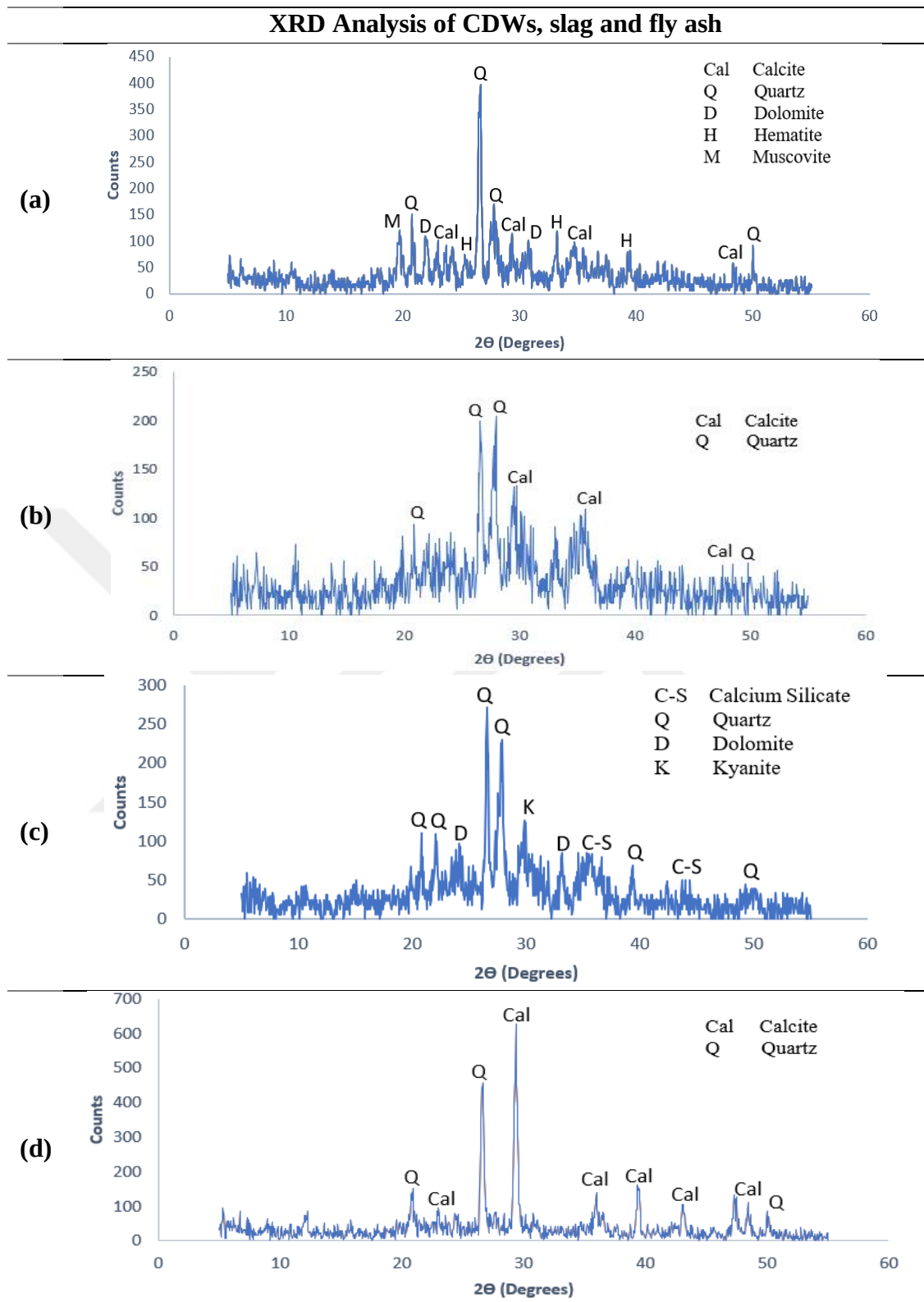


Figure 3.4. XRD Analysis of CDW-based materials: (a) Red Clay Brick, (b) Hollow Brick, (c) Roof Tile, (d) Concrete Waste, (e) Glass Waste, (f) GBFS and (g) FA

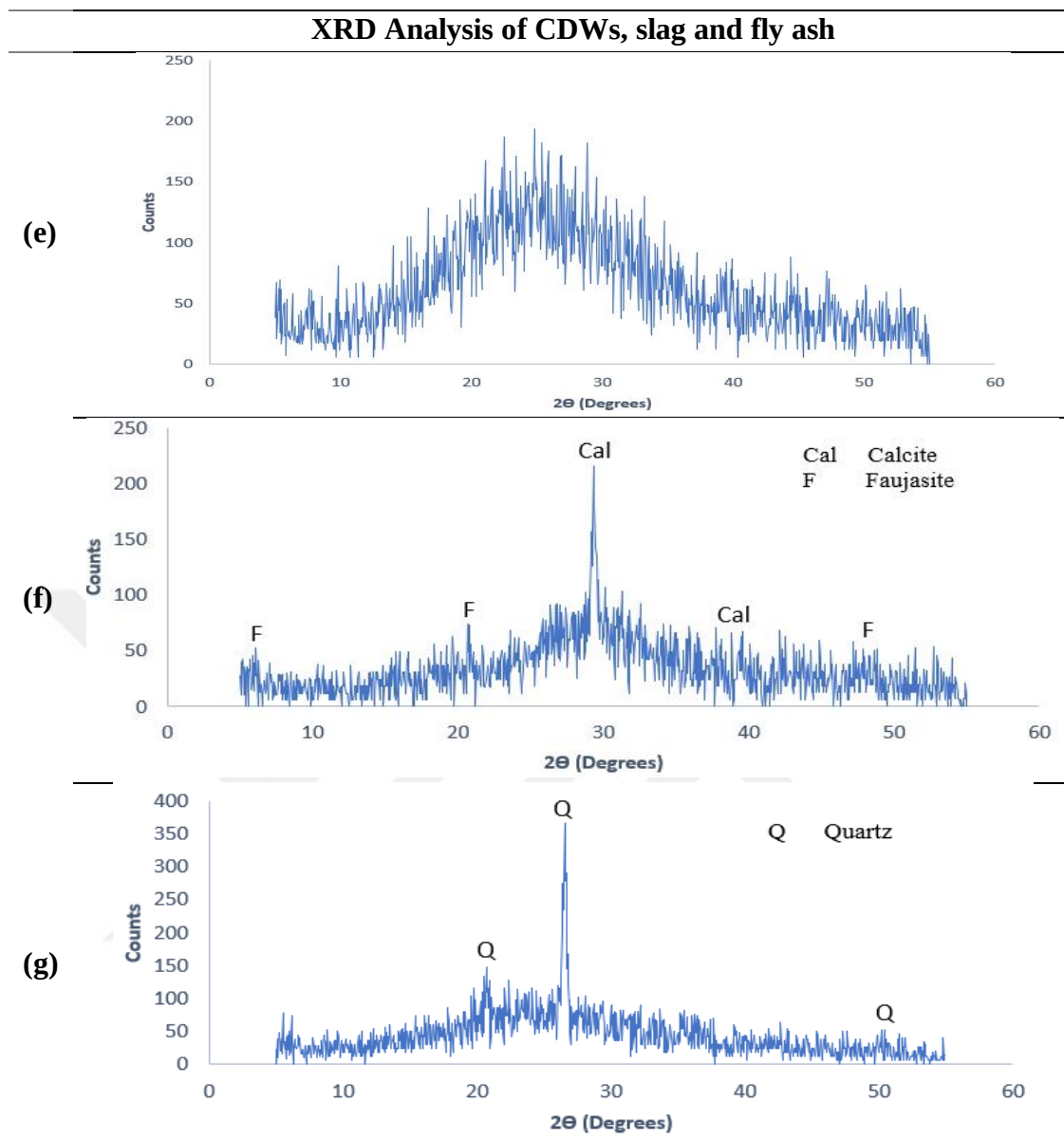


Figure 3.5. Continued.

Table 3.1. Chemical composition of CDWs, slag and fly ash

Chemical Composition (%)	SiO₂	Al₂O₃	Fe₂O₃	CaO	MgO	SO₃	TiO₂	K₂O	Na₂O	LOI
Hollow Brick	39.7	13.8	11.8	11.6	6.45	3.4	1.65	1.55	1.45	7.8
Red Clay Brick	41.7	17.3	11.3	7.69	6.49	1.41	1.57	2.66	1.15	7.96
Roof Tile	42.6	15.0	11.6	10.7	6.26	0.71	1.82	1.6	1.6	7.49
Glass Waste	66.50	0.93	0.25	10.00	3.93	0.24	0.06	0.20	13.60	4.15
Concrete Waste	31.60	4.76	3.50	31.30	5.12	0.92	0.24	0.71	0.45	20.90
Slag	32.1	11.2	0.62	36.10	5.64	1.21	1.07	0.83	0.31	9.09
Fly Ash	60.07	21.35	7.41	0.99	1.82	0.22	0.94	2.91	0.99	2.61

LOI: Loss of Ignition

According to the SEM images presented in Figure 3.3 of the CDWs used in the study, it is observed that the particles observed in 20 μm cross-section are quite similar to each other and do not have any specific characteristics. In addition, as it is known from the literature, fly ash has a spherical particle size. Thanks to this feature of fly ash, it is known that it reduces bleeding rate, prevents agglomerated of the main hydration product by entering between it and has a positive effect on workability with lubricating effect.

Looking at the XRD analysis results of the precursor materials presented in Figure 3.4, it is observed that all materials except glass waste have a crystalline microstructure. As it is known, the amorphous structure of the material and its low crystalline structure show positive results in terms of reactivity. Although the waste materials used in this study having various crystals such as high quartz and calcite that are negative in terms of reactivity, this problem can be partially eliminated with the optimum mixture and alkali activator design.

According to the results presented in Table 3.1, it was observed that the SiO₂ content of brick waste, glass waste and fly ash was high, while concrete waste and slag were rich in CaO. As it is known from the literature, optimizing the Si-Al-Ca balance in geopolymerization reactions is one of the most important criteria in improving the mechanical properties. Therefore, considering the chemical contents of the materials, these ratios have been tested in various ways in mixture optimization.

3.1.2. Alkali Activators

In the framework of the study, sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3) and calcium hydroxide ($\text{Ca}(\text{OH})_2$) were used as alkali activators. As it is known, due to the crystal nature and low reactivity of the precursors used for the production of geopolymer materials, sodium hydroxide provides high alkalinity and makes them ready for geopolymerization reactions by breaking the bonds such as SiO_2 , Al_2O_3 , CaO in the structure of the materials. Sodium hydroxide, which is prepared as a solution with water from 4M to 25M, is in the form of a flake by nature. Sodium silicate is in liquid form and increases the reaction rate and degree by releasing reactive SiO_2 and Na_2O into the environment during geopolymerization reactions. Calcium hydroxide, on the other hand, is also available in powder form and added directly to the mixture and gives extra strength by providing extra C-S-H and C-A-S-H gel formation due to its calcium content. Images of sodium hydroxide, sodium silicate and calcium hydroxide are presented in Figure 3.5.

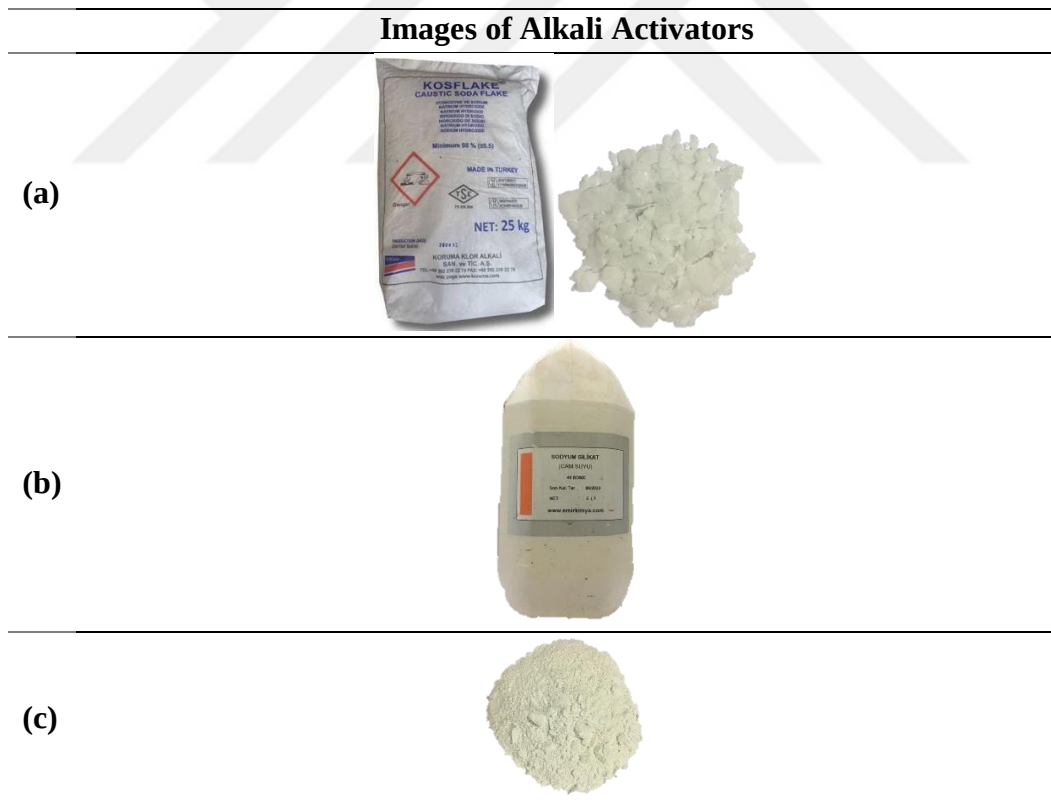


Figure 3.6. Images of Alkali Activators : (a) NaOH , (b) Na_2SiO_3 and (c) $\text{Ca}(\text{OH})_2$,

Chemical properties of sodium hydroxide, sodium silicate and calcium hydroxide are presented in Table 3.2-3.3-3.4, respectively.

Table 3.2. Chemical Properties of NaOH

Analyse	Property	Unit	Results
Appearance	White flake		White flake
NaOH	min. 98	%	98.26
NaCl	max. 0.11	%	0.03
Na₂CO₃	max. 0.41	%	0.34
Iron (Fe)	max. 16	ppm	13.18

Table 3.3. Chemical Properties of Na₂SiO₃

Parameter	Value
SiO₂ (%)	23
Na₂O (%)	11
Module (SiO₂/Na₂O)	2.09
Baume (20 °C, Be¹)	40
Density (20°C, gr/cm³)	1.40
H₂O (%)	66

Table 3.4. Chemical Properties of Ca(OH)₂

Analyzes	Results
Molecular Weight	74.1 g/mol
Melting Point	550 °C
Purity (%)	min. 88
MgO (%)	max. 1
Acid-insoluble (%)	max. 1
Loss of ignition (%)	max. 4
Particle size (<90 mm) (%)	min. 91

3.1.3. Aggregates

Within the scope of the study, normal aggregates in accordance with TS 706 EN 12620 standards were used as aggregate within the scope of this study. While 16 mm was chosen as the maximum aggregate size, it was designed to have a fine aggregate / coarse aggregate ratio of 1. The gradation curve of the aggregate is presented in Figure 3.6.

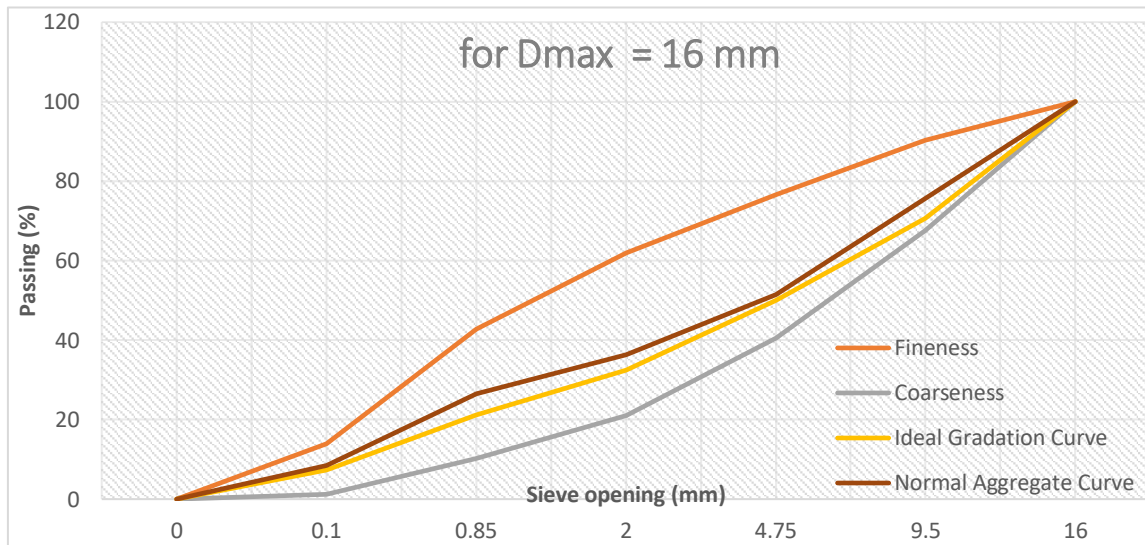


Figure 3.7. The gradation curve of the aggregate

3.1.4. Steel Bar

The properties of the steel bar used for reinforcement within the scope of the dissertation was given in Table 3.5.

Table 3.5 Properties of steel bar

Tension experiment of Steel bar			Ø6			Ø10		
			Specimen No.					
Property		Unit	1	2	3	4	5	6
D	Diameter	mm	6.42	6.52	6.48	10.4	10.1	10.38
	Average Diameter	mm	6.5			10.3		
A	Cross Sectional Area	cm	32.37	33.39	32.98	84.95	80.12	84.62
	Average Cross Sectional Area	mm²	32.9			83.2		
Py	Yield Load	kgf	1060	1100	1100	3900	3600	3900
σy	Yield strength kgf/mm2	kgf/mm²	327.4	329.4	333.5	459.1	449.3	460.8
	Average Fy	MPa	330.2			456.4		
Pw	Maximum Load kgf	kgf	1460	1500	1480	6150	5600	6150
Pw	Tensile Strength kgf/mm2	kgf/mm²	451	449.3	448.8	724	699	726.8
	Average Fu	MPa	449.7			716.6		
L	Grip Length	cm	70	70	70	100	100	100
S	Total Deformation	cm	23.13	26.32	24.23	19.73	19.07	19.66
	Deformation Percentage	%	33	37.6	34,6	19.7	19.1	19.7
	Average Deformation Percentage	%	35.1			19.5		
	Ribbed bar diameter calculation							
Specimen Dimensions								
			1	2	3	4	5	6
Specimen Weigth		gr	0.089	0.092	0.091	0.233	0.218	0.244
Specimen Length		cm	0.352	0,35	0,351	0,35	0,347	0.367
(KG/M) x (12.74) = Ø		mm	6.42	6.52	6.48	10.4	10.1	10.38

3.2. Methodology

The method of the experimental studies conducted within the scope of the thesis is explained below.

3.2.1. Preparation of Mixtures

The mixtures designed in the study were weighed separately in the solid and liquid phases before mixing with 0.1 g sensitivity. The sodium hydroxide used in the liquid phase was mixed with water to achieve the targeted molarity value and allowed to cool at room conditions for one day. Since sodium silicate is in the liquid solution phase, it was added directly to the mixture.

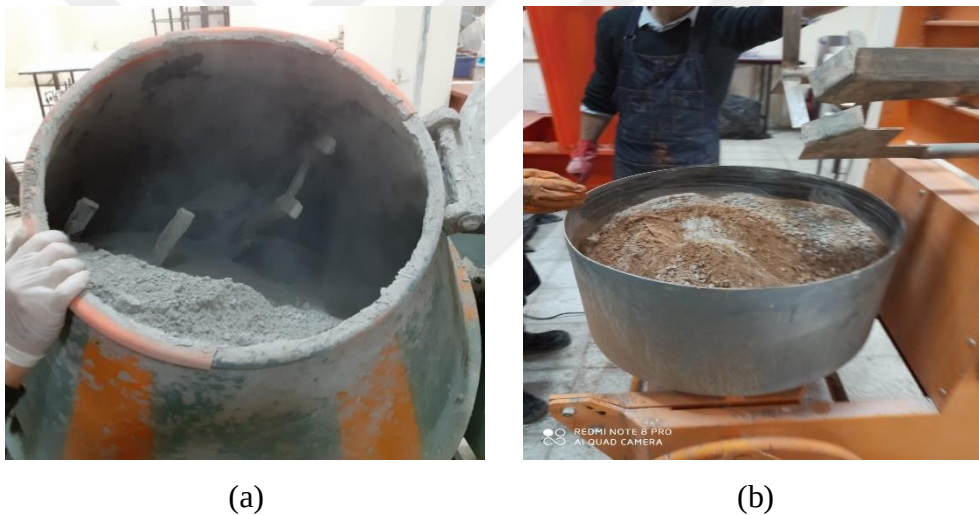


Figure 3.8. Preparation of dry mixtures, (a) concrete mixture, (b) geopolymer mixture.

3.2.2. Casting and Placing

After the preparation of the dry and liquid mixtures, the dry mixture was poured into the mixer in a volume of 40 liters and mixed for 1 minute. Then, sodium hydroxide solution was included slowly and mixed for 2 minutes. Finally, sodium silicate was included and the mixing process was finished after 2 minutes of final mixing. After the mixing process was completed, the materials were poured into the prepared molds and compacted by a vibrator.

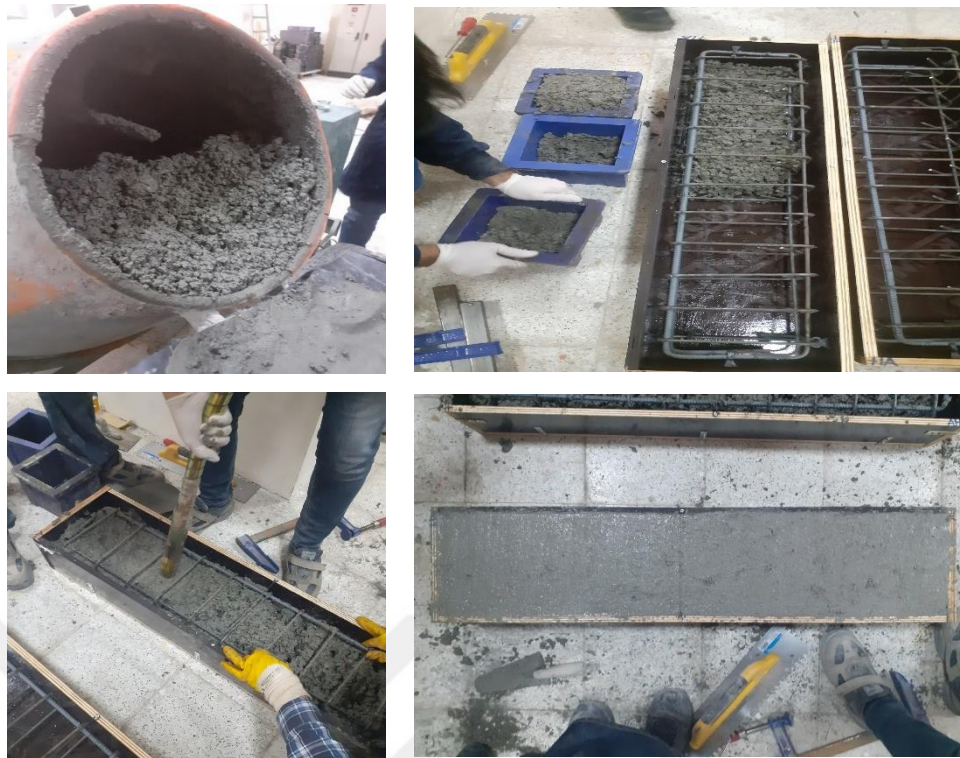


Figure 3.9. Casting and placing process of concrete mixtures



Figure 3.10. Casting and placing process of geopolymer mixtures

3.2.3. Curing Conditions

Within the scope of this study, cube, cylinder and beam samples were removed from the mold one day after the casting, and cured in the water pool in order to prevent water loss and drying shrinkage and to ensure the continuation of geopolymerization reactions. In addition, since the geopolymers showed shrinkage cracks in the ambient conditions during the preliminary studies, these cracks were prevented by water curing. Apart from geopolymers, concrete samples were covered and applied moisture-curing until the test day.



Figure 3.11. Curing of the specimens, (a) concrete samples, (b) geopolymer samples

3.3. Experimental Test Setup and Test Specimens

This section includes parameters such as the dimensions, shear-span to depth ratios (a/d), reinforcement of the test specimens.

Within the scope of this study, to examine of the structural behavior of concrete and geopolymer, cube specimens with dimensions of $15 \times 15 \times 15$ cm, cylindrical specimens with dimensions of 30 cm length and 15 cm diameter and 20 cm length and 10 cm diameter and beam specimens with dimensions of $110 \times 25 \times 15$ cm were produced. Cube samples were produced 3 specimens for each mixture, and the 28-day compressive strength was measured by setting the machine's set speed as 3 kN/s, preload value as 10 kN and preload speed as 40%. Cylindrical samples were produced 3 specimens of each mixture to measure the

splitting-tensile strength at 28 days. Within the scope of this study, 3 shear-critical beams with dimensions of 1100×250×150 mm were produced as reference samples to compare with geopolymer beams. The distances between stirrups are 200 mm. In order to examine different failure modes in beam samples, three different a/d ratios (0.49, 1.00, and 1.65) were used in shear-critical beams. The physical properties of the closed system used to obtain these values were effective. Also, among the selected a/d ratios, the smallest was predicted to examine the pure shear failure, combined shear-flexure failure mode.

During every test, a displacement-controlled hydraulic actuator was used to implement two-point vertical loads on simply supported beam specimens. In this context, the vertical force was recorded, and the midspan vertical displacement was measured using Linear Variable Differential Transformers (LVDTs).

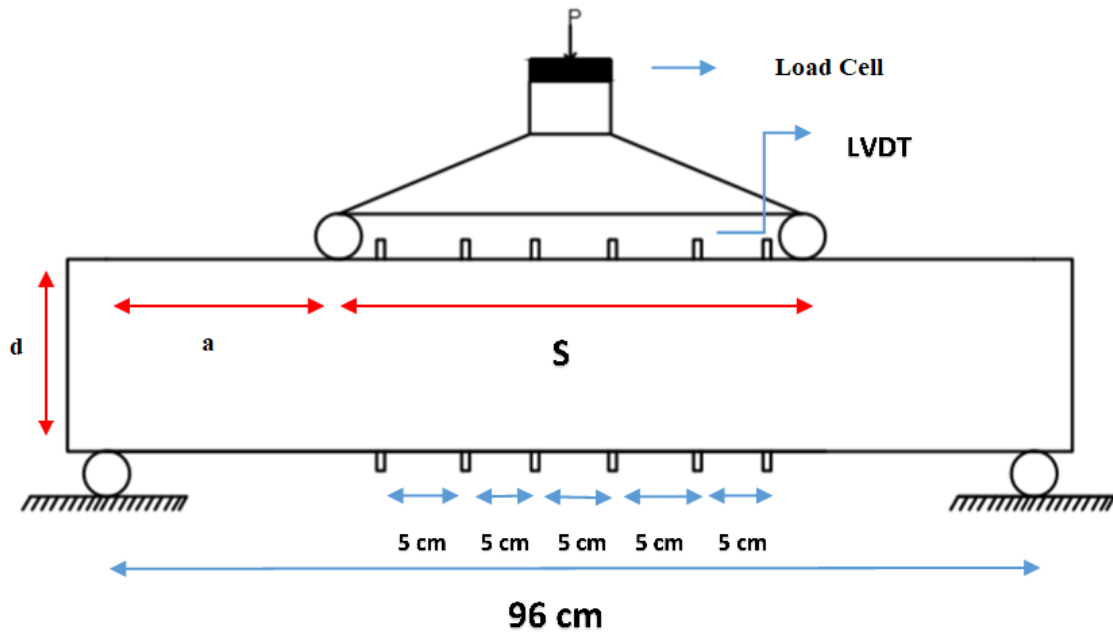


Figure 3.12. Graphical representation of the test setup

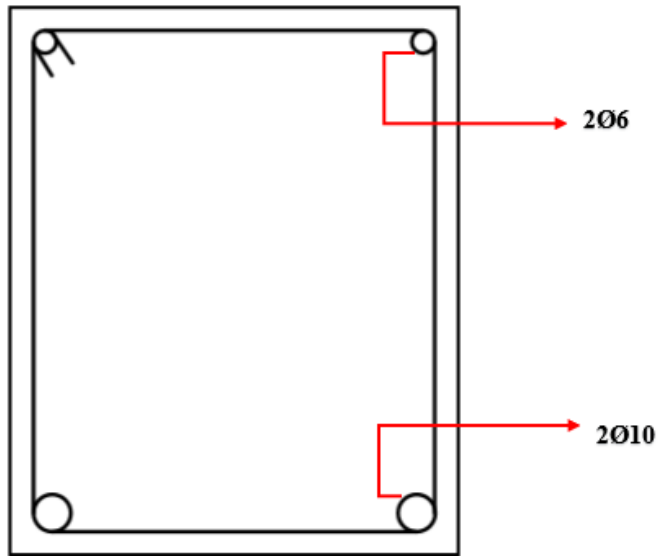


Figure 3.13. Reinforcement details



Figure 3.14. Reinforcement details



Figure 3.15. Test specimens before experiment

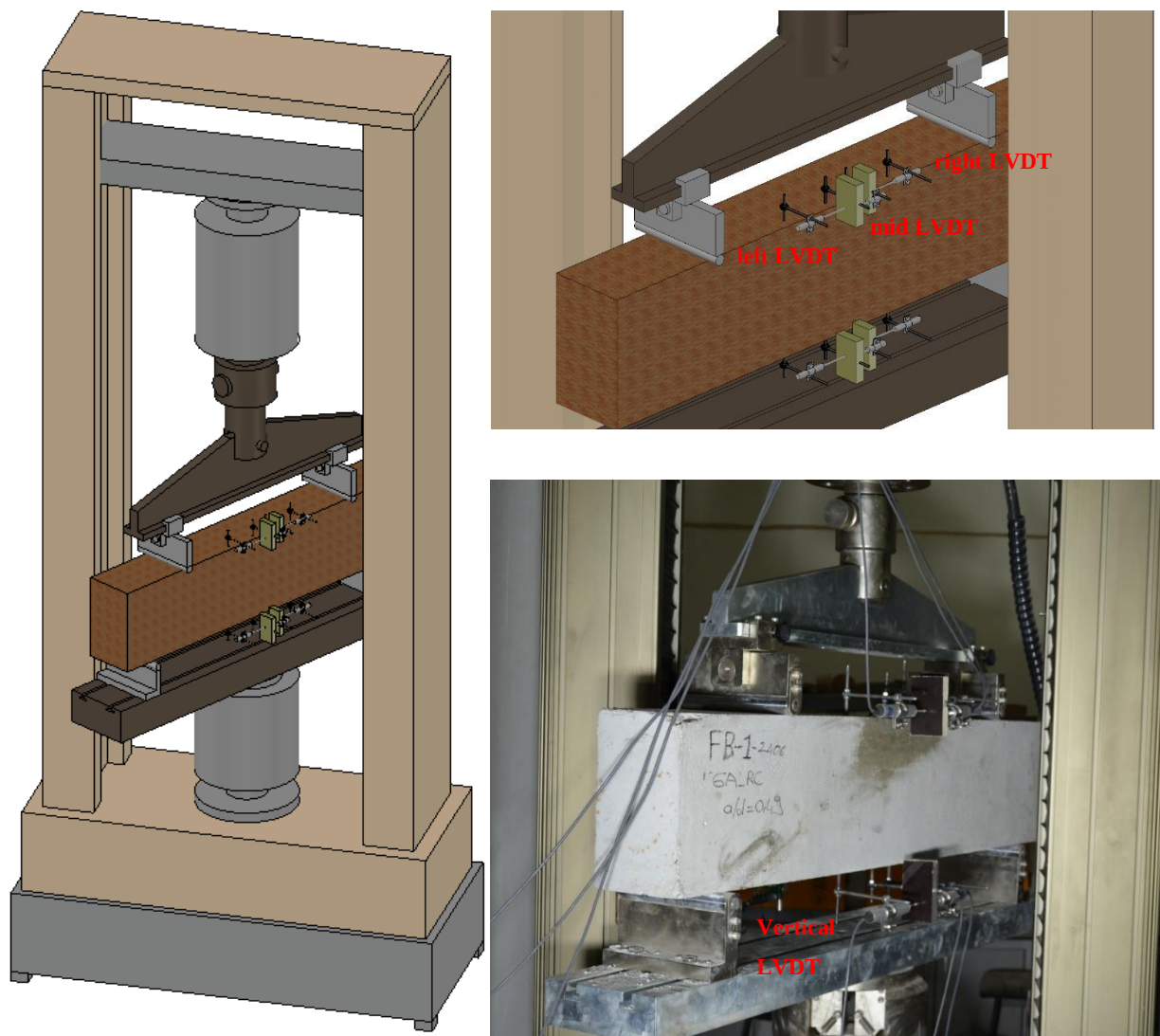


Figure 3.16 Test Setup and Instrumentation

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

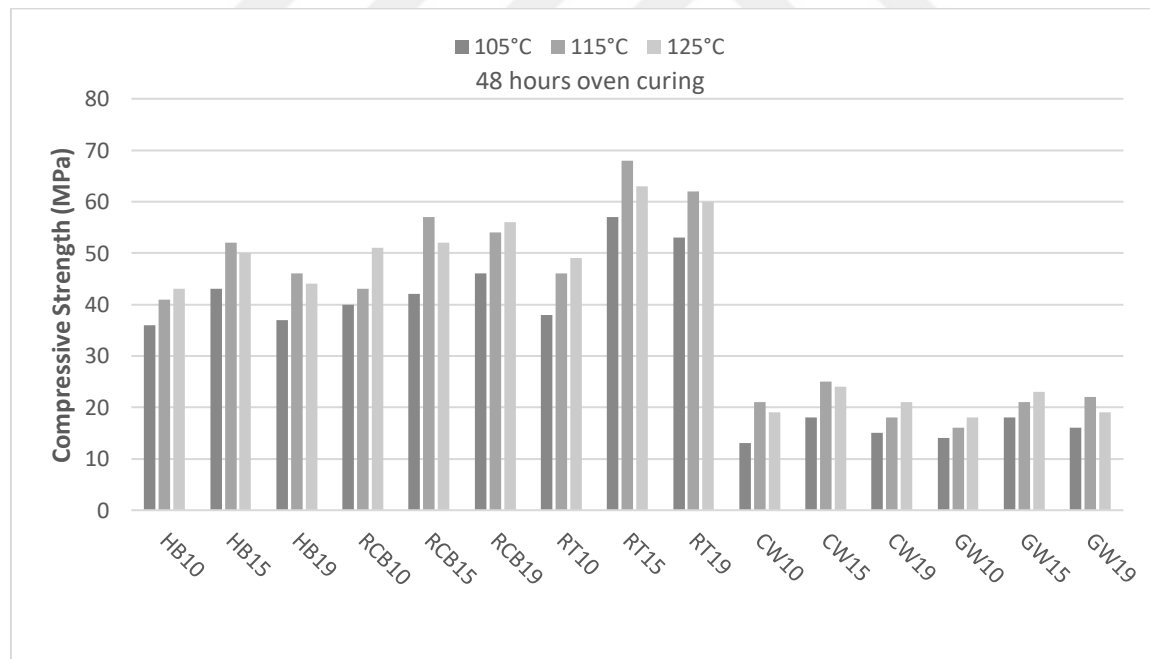
4.1. Development of Geopolymer Concretes

Before the geopolymer beam design, a preliminary study was conducted to verify the feasibility of geopolymer binders using construction demolition waste as the main aluminosilicate source. The easiest and most effective method to understand geopolymer structure is formed is to measure the compressive strength. More reactions in the matrix result in a denser microstructure followed by higher compressive strength results. For this reason, compressive strength tests were carried out to develop the paste phases and to conduct performance evaluations. After the extensive literature analysis, sodium hydroxide was selected as an alkali activator in the preliminary studies on geopolymer matrix design. In this context, CDW-based materials were activated with various sodium hydroxide molarities individually. In this stage, various geopolymer paste mixtures were produced using alkali activator solutions prepared at three different sodium molarities (10M, 15M, and 19M) with tile and brick powders (RT, RCB and HB), concrete waste and glass waste. For the prepared paste mixtures, the W/B ratio was chosen as 0.35, and the compressive strength tests were performed after the samples removed from the mold were left at three different temperatures (105 ° C, 115 ° C, 125 ° C) and 48 hours duration. The sodium hydroxide molarity and thermal curing temperature used in the mixtures were determined by extensive literature research and various trial mixes. Within the scope of preliminary studies, the production was carried out by observing the consistency of the pastes produced in the fresh mixture, their workability, whether they hardened depending on the thermal curing temperature, crack formation, easy removal from the mold, the effects of the waiting time after mixing the activator. Mixing ratios are presented in Table 4.1, and compressive strengths are shown in Figure 4.1.

Table 4.1 Mixture designs of CDW-based geopolymer pastes

Code	HB	RCB	RT	CW	GW	Na(OH)	Water	Na (M)
HB10	1600					224	560	10
HB15	1600					336	560	15
HB19	1600					425.6	560	19
RCB10		1600				224	560	10
RCB15		1600				336	560	15
RCB19		1600				425.6	560	19
RT10			1600			224	560	10
RT15			1600			336	560	15
RT19			1600			425.6	560	19
CW10				1600		224	560	10
CW15				1600		336	560	15
CW19				1600		425.6	560	19
GW10					1600	224	560	10
GW15					1600	336	560	15
GW19					1600	425.6	560	19

Note: The unit of all materials is kg/m³. M: Molarity

**Figure 4.1** Compressive strength results of CDW-based geopolymer pastes

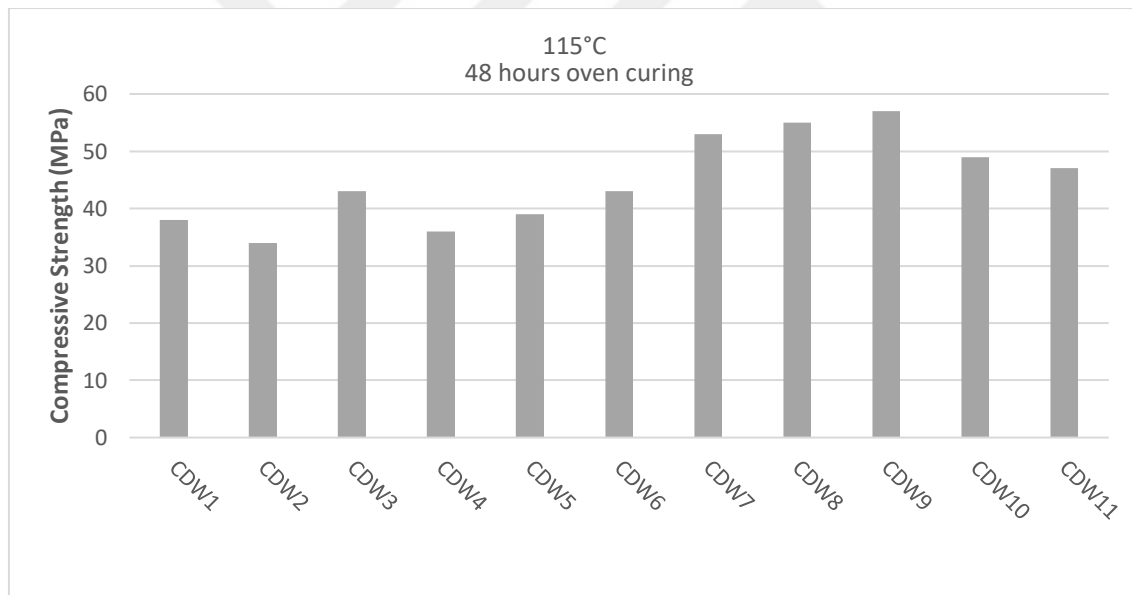
According to the results given in Figure 4.1, it was seen that the strengths of mixtures containing roof tiles, hollow bricks, and red clay bricks exhibited the lowest strengths at 10 molarity sodium hydroxide concentration. It has been observed that the strength significantly

increases when the sodium concentration is increased to 15 molarity. When the alkali activator, which enables the dissolution of aluminosilicate-based waste materials during the reaction, is used at high concentrations, it causes an increase in polymerization reactions and triggers the formation of a higher rate of N-A-S-(H) in the matrix and thus has a positive effect on the performance (Ahmari et al., 2012). When the sodium concentration was increased to 19 molarity, the strength of the many mixtures tended to decrease. The high rate of increases in alkali concentrations after a point significantly hinders the geopolymer mechanism. The diffusion of alkali ions with low mobility from the solution is considerably reduced. Another reason for this situation is that the formation of quick and inhomogeneous reaction products in the mixtures produced with high alkali concentrations. These reaction kinematics are harmful to the performance of the final product (Palomo et al., 2004). The strengths of mixtures containing concrete waste exhibited the lowest strengths at 10 molarity sodium concentration, similar to brick powders. The strengths of mixtures containing glass waste exhibited the highest strengths at 15 molarity sodium concentration, unlike other waste materials. In addition to the role of alkali activator concentration on the strength, it was observed that the thermal curing temperatures applied to the samples also had a great effect on the strength of the final product. When the results are examined in general, the temperature increase generally increases the strength of the samples. The increment in thermal curing heats accelerates polymerization reactions and enables the geopolymer paste to reach high compressive strengths in a short time. However, high temperatures applied after a certain point cause moisture loss in the samples, causing an inhomogeneous matrix with a high void ratio, resulting in a decrease in compressive strength. In addition, high temperature causes shrinkage by creating excessive volume loss in samples, and this causes shrinkage cracks in the samples, leading to low performance of the final products.

Table 4.2 Mixture designs of CDW-based geopolymer paste combinations

Code	HB	RCB	RT	CW	GW	Na(OH)	Water	Na (M)
CDW1	320	320	320	320	320	336	560	15
CDW2	426.67	213.33	320	320	320	336	560	15
CDW3	213.33	320	426.67	320	320	336	560	15
CDW4	142.13	213.33	284.53	480	480	336	560	15
CDW5	177.87	266.67	355.47	400	400	336	560	15
CDW6	248.80	373.33	497.87	240	240	336	560	15
CDW7	284.53	426.67	568.80	160	160	336	560	15
CDW8	284.53	426.67	568.80	106.67	213.33	336	560	15
CDW9	284.53	426.67	568.80	80	240	336	560	15
CDW10	284.53	426.67	568.80	213.33	106.67	336	560	15
CDW11	284.53	426.67	568.80	240	80	336	560	15

Note: The unit of all materials is kg/m³. M: Molarity

**Figure 4.2** Compressive strength results of CDW-based geopolymer paste combinations

In this part of the preliminary studies conducted within the scope of the design of geopolymer beam samples, some mixture designs were made by combining CDW-based wastes together. The compressive strengths of these mixtures, which were prepared by using each brick waste together with concrete and glass waste in various proportions, were measured, and it was aimed to use the mixture with the best strength in the final geopolymer beam design. However, some waste materials that were found to exhibit low strength results were

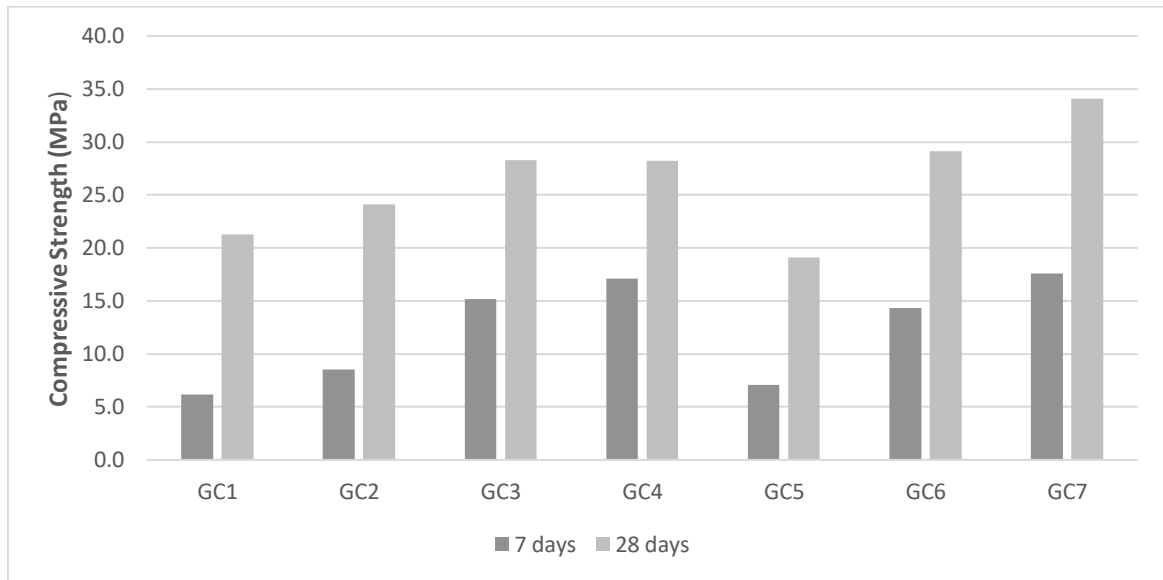
substituted at low rates instead of being removed from the mixture, and it was aimed at completely recycled CDW-based materials into a realistic approach. According to the results presented in Fig. 4.2, the CDW9 coded mix exhibited the highest compressive strength performance with 57 MPa. Considering the content of the CDW9 coded mixture, it was seen that roof tile was used at the highest rate, followed by red clay brick and hollow brick, respectively. In addition, 15% of CW and 5% of GW were used in the mixture. It has been stated in the literature studies that the reason for the high performance of brick powders compared to concrete and glass powders is due to the fact that they are more suitable aluminosilicate-based source materials in terms of geopolymerization, content, and size (Allahverdi and Najafi Kani, 2009). After obtained as a result of mixing aluminosilicate-based waste materials within the scope of preliminary studies, the optimum ratios of five different CDW materials, which will form the basis of the geopolymer concrete and beam mixtures to be produced in the following part of the study, were determined and information was obtained about the behavior of geopolymer reactions by looking at their mechanical properties.

After testing the geopolymerization mechanisms and compressive strengths of CDW-based waste materials as a single and a combination, the design of geopolymer concrete mixtures was studied in the next stage of the study. In this context, various mixture designs were made by including the graded fine and coarse aggregates into the system. In addition, according to the information obtained from some study results and literature reviews, sodium silicate and calcium hydroxide were added to the geopolymer concretes to be developed in ambient curing, and blast furnace slag and fly ash were added at various rates. In this context, the geopolymer concrete mixture designs and compressive strength results were given in Table 4.3 and Figure 4.3, respectively.

Table 4.3 Mixture designs of CDW-based geopolymer concrete

Code	HB	RCB	RT	GW	CW	GBFS	FA	Ca(OH) ₂	NaOH	Na ₂ SiO ₃	Aggregate	Water
GC1	187.5	250	312.5	125	125	0	0	0	112	224	1000	202.15
GC2	187.5	250	312.5	125	125	0	0	75	112	224	1000	202.15
GC3	150	200	250	100	100	200	0	50	112	112	1000	276.1
GC4	150	200	250	100	100	150	50	50	112	112	1000	276.1
GC5	150	200	250	100	100	150	50	100	168	0	1000	350
GC6	150	200	250	100	100	150	50	50	112	112	2000	276.1
GC7	150	200	250	100	100	150	50	50	112	224	1000	202.15

Note: The unit of all materials is kg/m³.

**Figure 4.3** Compressive strength results of CDW-based geopolymer concrete

Considering the results presented in Figure 4.3, the GC7 coded mixture showed the best performance by exhibiting 34.1 MPa at the end of 28 days. When the mixture contents are examined in general, it is seen that the addition of blast furnace slag has a positive effect on strength. This is related to the high calcium content in the slag that increases matrix strength by triggering the formation of extra C-S-H and C-A-S-H gels by dissolving in the system (Yip et al., 2005). In addition, Ca(OH)₂, which is also included in the system as a third activator, provides the ion balance of the matrix and triggers the formation of a calcium-based gel, as it is a source of soluble calcium. On the other hand, due to the spherical grain structure of the fly ash, the use of extra water or plasticizer was prevented by using a low volume of fly ash due to the increase in workability. Considering the alkali activator

combinations designed in geopolymer concrete mixtures, it is observed that the use of sodium silicate has a high amount of positive mechanical properties. Contrary to the thermal curing applied in geopolymer paste designs, sodium hydroxide alone was not sufficient to achieve high strength since ambient curing was applied in this series. Therefore, as a result of literature reviews and preliminary studies, it was decided to use sodium silicate in the mixtures, and the highest strength result was obtained by using the amount of sodium silicate in the GC7 coded mixture to be two times the amount of sodium hydroxide. It has been observed that sodium silicate, which has an excessive reactive and soluble silicate content, significantly supports the geopolymerization kinetics in early reaction and enables high strengths to be reached quickly. According to the results, it was decided to use the GC7 coded mixture for the next parts of the study.

4.2. Development of Geopolymer Beams

In this section, geopolymer beam designs were developed in the context of the thesis study following the development of geopolymer mixture designs. In this context, three shear-critical geopolymer beams with dimensions of $1100 \times 250 \times 150$ mm were produced with the optimum geopolymer mixture determined by preliminary studies. During the producing geopolymer beam samples, it was produced cubic and cylindrical samples additionally to measure the other characteristics properties of geopolymer. In this context, the mixture design of the final geopolymer product was presented in Table 4.4.

Table 4.4 Mixture design of final product of geopolymer

Code	HB	RCB	RT	GW	CW	GBFS	FA	Ca(OH) ₂	NaOH	Na ₂ SiO ₃	Aggregate	Water
GC	150	200	250	100	100	150	50	50	112	224	1000	202.15

Note: The unit of all materials is kg/m³.

4.2.1. Compressive and Splitting-Tensile Strength of Geopolymer

Within the scope of the production of geopolymer beam samples, three cubic samples of $150 \times 150 \times 150$ mm were produced in order to test their compressive strength. The produced samples were broken on various days, and their compressive strength was measured. The compressive strength test setup is presented in Figure 4.4, and the strength results are presented in Table 4.5.

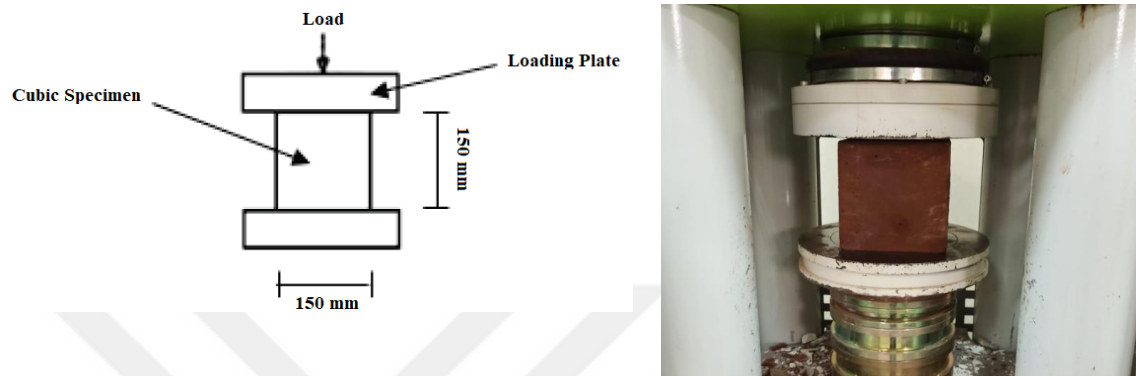


Figure 4.4 Compressive Strength Test Setup and Experiment

Table 4.5 Compressive Strength Results of Geopolymer Concrete

Test Period	7. day	14. day	28. day
Compressive Strength (MPa)	24	28.5	32.1

According to the Table 4.5, it was observed that the mixture hardened with a very high acceleration in 7 days and reached a high early strength such as 24 MPa. In addition, the final product chosen in the development of geopolymer concrete mixtures reached a very high value with a 32.1 MPa in 28 days, similarly under ambient conditions.

In addition, for the measure of the splitting-tensile strength of the final geopolymer mixture, cylindrical specimens were produced. The images of the geopolymer cylindrical specimens produced with 150 mm diameter and 300 mm height dimensions are presented in Figure 4.5, and the splitting-tensile strength results are presented in Table 4.6. The formula given below is used for calculating the splitting-tensile strength of the specimens:

$$\sigma = \frac{2P}{\pi \times L \times D}$$

where,

σ : Splitting-Tensile Strength (MPa)

D: Diameter of the cylinder sample (mm).

L: Length of the cylinder sample (mm),

P: Failure load of the cylinder sample (N),

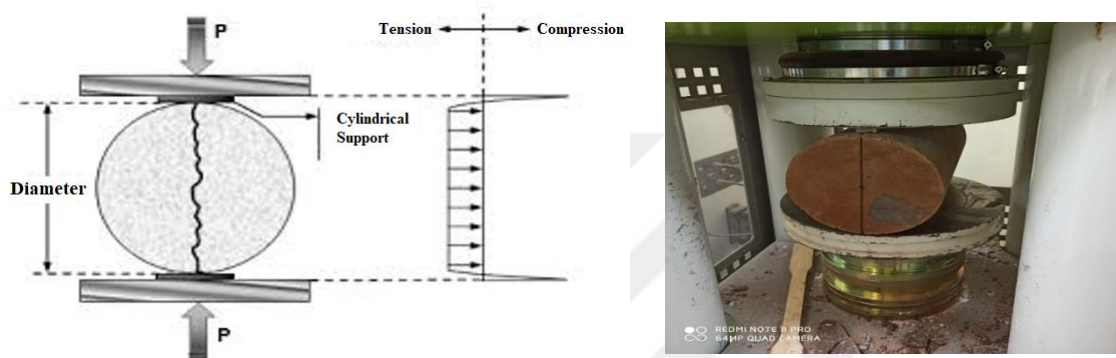


Figure 4.5 Splitting-Tensile Strength Test Setup and Experiment

Table 4.6 Splitting-Tensile Strength Results of Geopolymer Concrete

Code	#1	#2	#3	#4	#5
Splitting-Tensile Strength (MPa)	2.09	2.35	2.35	2.38	2.41

According to the splitting-tensile strength results of geopolymer specimens presented in Table 4.6, the samples exhibited a strength ranging from 2.09 MPa to 2.41 MPa after 28 days. Although datas obtained do not show the exact tensile strength of the geopolymer samples, it is important to give an idea. These results will provide important information about the relationship between the bending and shear behavior of geopolymer beam samples in terms of material effect.

4.2.2. Shear-Critical Geopolymer Beam #1

The geopolymer beams planned to be produced within the scope of the thesis study were designed as shear-critical as mentioned before. Shear-critical geopolymer beam #1 sample was produced by determining the stirrup distance as 200 mm for geopolymer beams designed as shear-critical. The a/d ratio of this beam was determined as 0.49. Before the geopolymer was poured, the reinforcement system weighed 4 kg, and the weight of the geopolymer beam was 97 kg in the weighing made before the experiment. The volumes of all cast beams are constant and are 0.04125 m^3 . The density of this beam has been calculated as 2351.51 kg/m^3 . Shear cracks were observed during the experiment. At the point where the shear crack that occurred during the experiment cracked all of the concrete between the support and load region, and the sample has lost its full capacity. The image of the Shear-Critical Geopolymer Beam #1 during the experiment presented in Figure 4.6 and the image of the crack formation of the Shear-Critical Geopolymer Beam #1 during the experiment were given in Figure 4.7-4.8, respectively.



Figure 4.6 The image of the Shear-Critical Geopolymer Beam #1 during the experiment

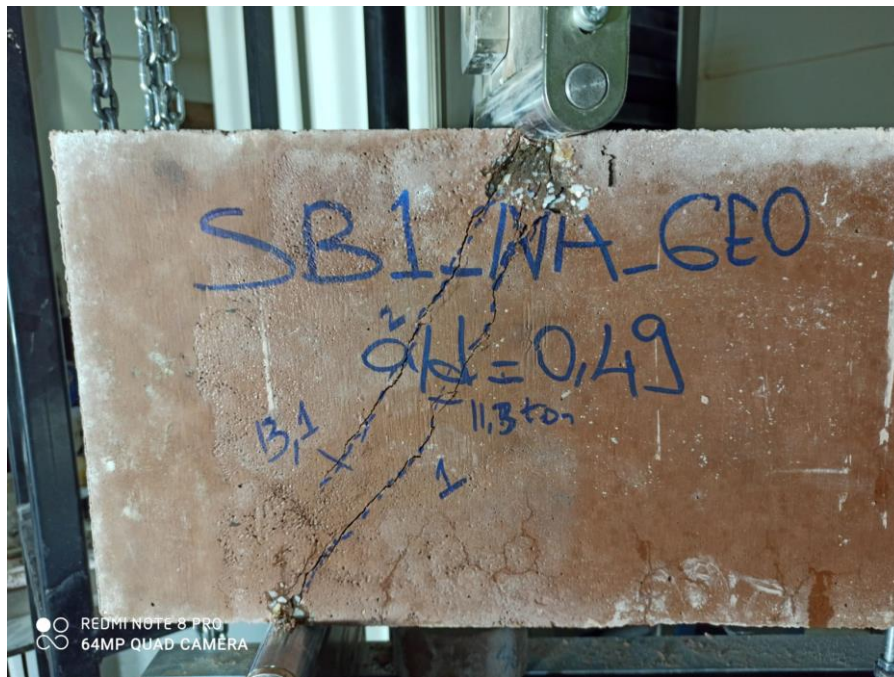


Figure 4.7 Shear crack formation in the support area



Figure 4.8 Growth of shear crack in the support area



Figure 4.9 Large shear crack at the back of the specimen after the test

Moment-curvature and load-deformation graphs of the Shear-Critical Geopolymer Beam #1 are presented in Figures 4.10-4.11, respectively.

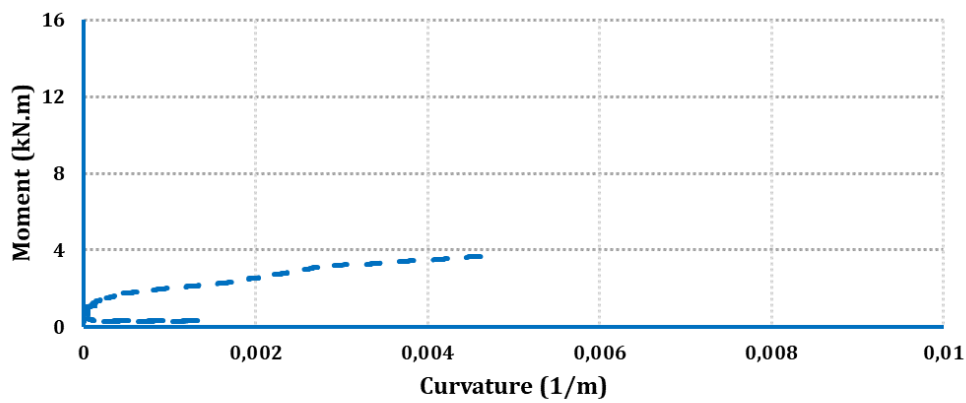


Figure 4.10 Moment-curvature results of the Shear-Critical Geopolymer Beam #1

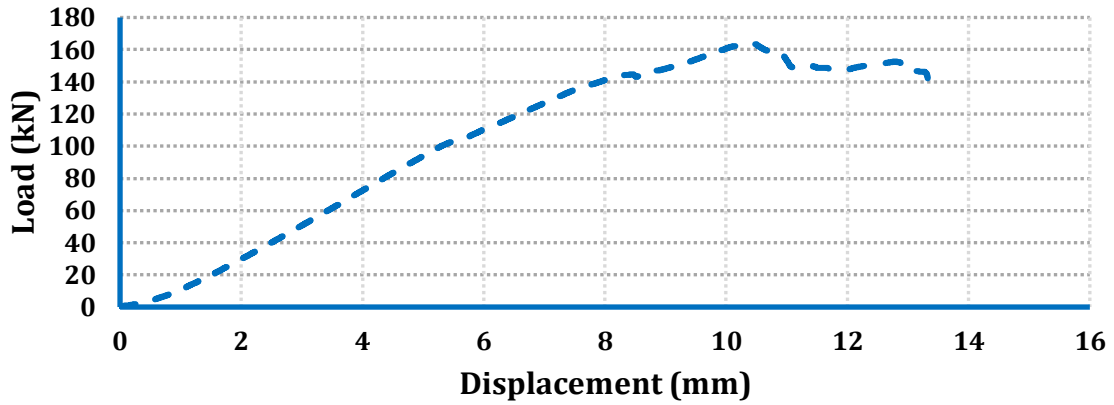


Figure 4.11 Load-Displacement results of the Shear-Critical Geopolymer Beam #1

According to the results obtained from the geopolymer beam tests with a 0.50 a/d ratio, it was observed that the beams experienced shear-failure mode. It has been observed that the beams exhibit crack formation behavior in the shear span during the test period. This situation, as can be seen in Figure 4.7, caused the crack growing near the support to eventually result in a shear failure near the support. Thus, the moment-curvature graphs exhibited a little deviation from the linear range. As given in Figure 4.11, the geopolymer beam had a maximum load-carrying capacity of 162.75 kN, according to the load-displacement graph. The beam sample, which made a displacement of approximately 10.53 mm in response to this load value, showed a displacement behavior of a maximum of 13.442 mm at the failure stage.

4.2.3. Shear-Critical Geopolymer Beam #2

In the shear-critical geopolymer beam #2, the stirrup distance was determined as 200 mm, and the span distance was set as 245 mm in the setup. This value corresponds to an a/d ratio of 1.00. The reinforcement system before pouring the geopolymer weighed 4 kg, and the weight of the reinforced geopolymer beam was 96 kg in the weighing made before the test. The volumes of all cast beams are constant and are 0.04125 m³. The density of this beam has been calculated as 2327.27 kg/m³. During the experiment, initial bending cracks and then shear cracks were observed. As a result of the experiment, the images of the cracks formed in the anterior and posterior regions are shown in Figure 4.12-13.



Figure 4.12 5 mm wide shear crack formation in the anterior between support



Figure 4.13 10 mm wide shear crack formation in the posterior between supports

Moment-curvature and load-deformation graphs of the Shear-Critical Geopolymer Beam #2 was given in Figure 4.14-4.15, respectively.

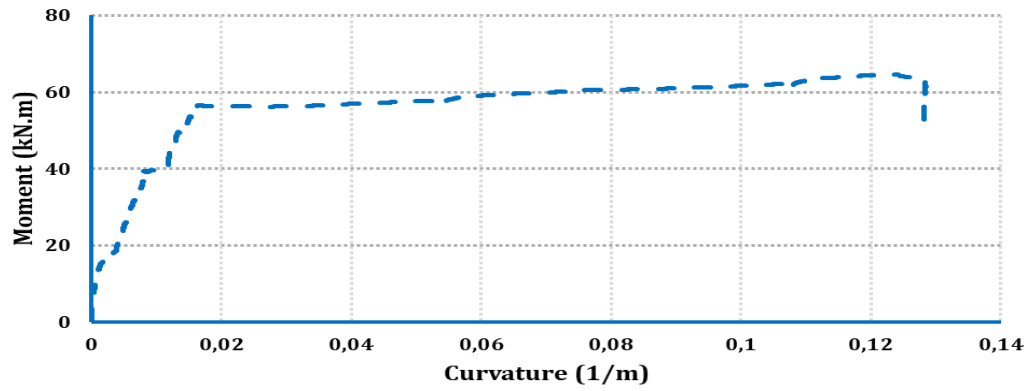


Figure 4.14 Moment-curvature results of the Shear-Critical Geopolymer Beam #2

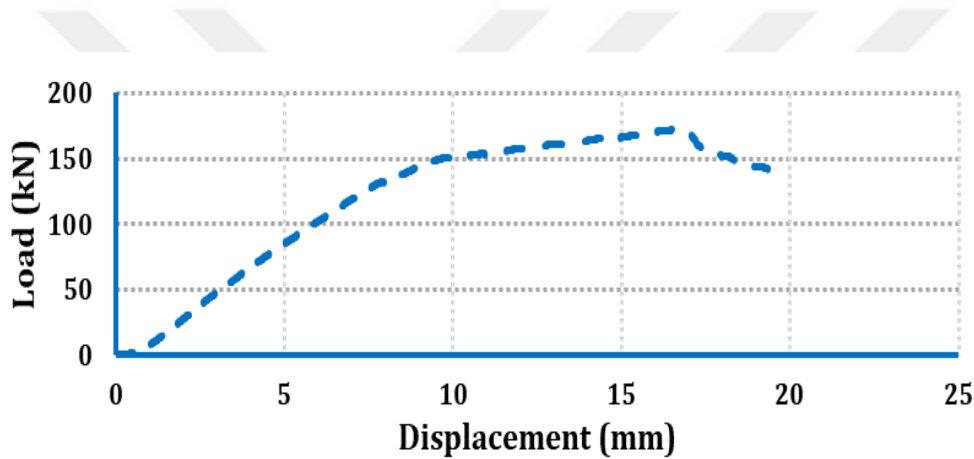


Figure 4.15 Load-Displacement results of the Shear-Critical Geopolymer Beam #2

According to the results given in Figure 4.14 and Figure 4.15, it was seen that the geopolymer beams with an a/d ratio of 1.00 also failed in shear-dominated action, similar to the previous series. Considering the results, it was seen that Shear-critical geopolymer beam #2 exhibits a very brittle material behavior. In addition, the samples exhibited a limited or no post-yield response behavior. This situation was supported by the formation of a very wide crack with 5 mm width and causing failure in the vicinity of the support shown in Figure 4.12. Additionally, according to the load-displacement results presented in Figure 4.15, it was seen that the maximum load capacity of geopolymer beam is approximately 165 kN and maximum displacement capacity is around 19 mm. These results showed that increasing the a/d ratio from 0.49 to 1.00 results in an increase in the load and displacement capacities.

4.2.4. Shear-Critical Geopolymer Beam #3

In the shear-critical geopolymer beam #3, the stirrup distance was determined as 200 mm, and the span distance was set as 405 mm in the setup. This value corresponds to an a/d ratio of 1.65. The reinforcement system before pouring the geopolymer weighed 4 kg, and the weight of the reinforced geopolymer beam was 96 kg in the weighing made before the test. The volumes of all cast beams are constant and are 0.04125 m^3 . The density of this beam has been calculated as 2327.27 kg/m^3 . During the experiment, initial bending cracks and then shear cracks were observed similar to Shear-critical geopolymer beam #2. As a result of the experiment, the images of the cracks formed in the anterior and posterior regions are presented in Figures 4.16-19.



Figure 4.16 The image of the Shear-Critical Geopolymer Beam #3 during the experiment

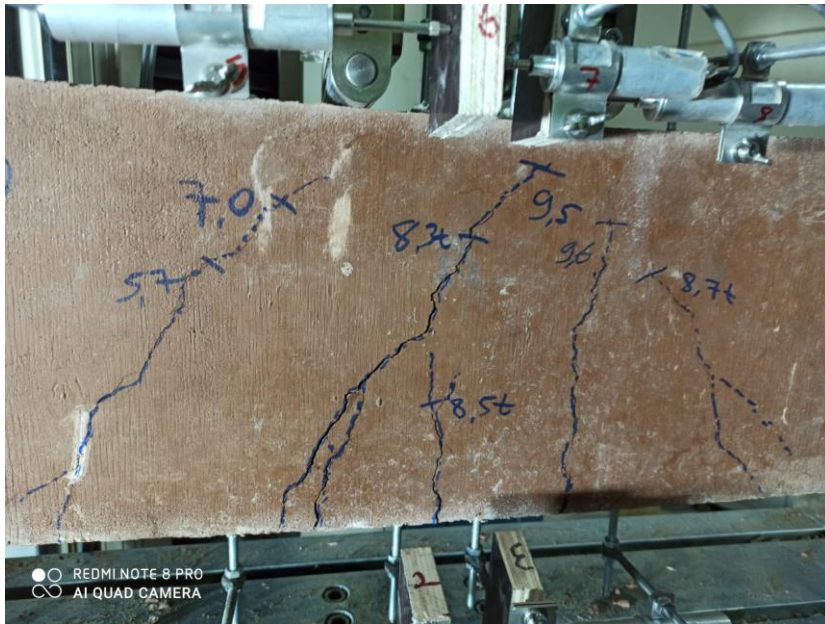


Figure 4.17 Crack formation at the front of the specimen



Figure 4.18 Growth of the cracks at the fron of the specimen



Figure 4.19 Large cracks at the back of the specimen after test

Moment-curvature and load-deformation graphs of the Shear-Critical Geopolymer Beam #3 are presented in Figure 4.20-21, respectively.

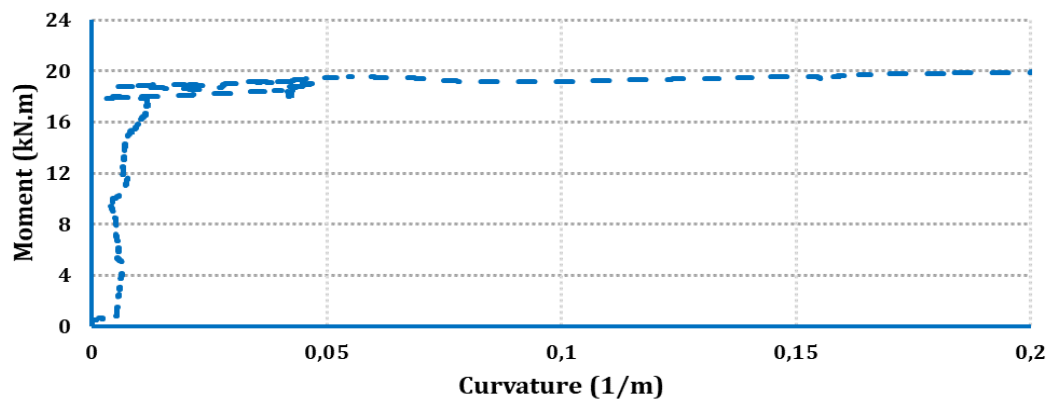


Figure 4.20 Moment-curvature results of the Shear-Critical Geopolymer Beam #3

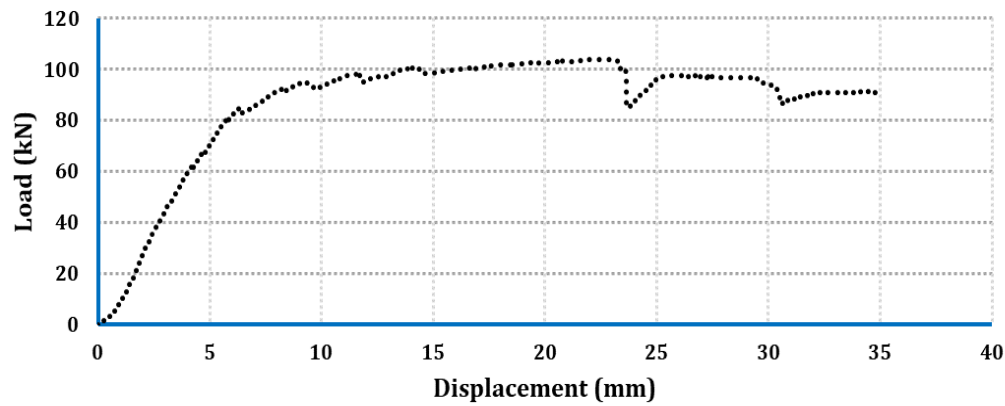


Figure 4.21 Load-Displacement results of the Shear-Critical Geopolymer Beam #3

Considering the behavior of Shear-Critical Geopolymer Beam #3 with an a/d ratio of 1.65 under bending load, it was observed that all samples failed in shear-flexural failure mode as expected. In addition, it should be noted that specimens lost their bearing capacity due to the enlargement of inclined cracks. This situation can be verified by looking at the width of the cracks formed in the anterior and posterior regions presented in Figure 4.16 and Figure 4.17. On the other hand, when looking at the load-displacement plot of Shear-Critical Geopolymer Beam #3, it can be said that it has a load-carrying capacity of a maximum 100 kN and shows a displacement value that can reach 35 mm values under this constant load during the test. In addition to this, unlike other geopolymer beam series, in the a/d ratio of 1.65, a decrease in load parameter was observed, while a significant increase in displacement value was observed. This situation may be associated with the failure mode being closer to the flexural and showing a more ductile property.

4.3. Development of Concrete Beams

In this part of the study, conventional Portland cement beam samples with similar compressive strength with the geopolymer were produced for compare the mechanical properties of the developed new generation CDW-based geopolymer beams. Cementitious beams have also been subjected to four-point bending tests as in geopolymer beams. As a result of the test, moment-curvature and load-displacement graphs of the beams were

obtained. The design of mixtures produced with conventional cement is presented in Table 4.7.

Table 4.7 Mixture design of Conventional Concrete

Material	Cement	Fine Aggregate	Coarse Aggregate	Water	Water/Binder
PC	316	917	917	211	0.67

Note: The unit of all materials is kg/m³.

4.3.1. Compressive and Splitting-Tensile Strength of Concrete

For the measure the compressive strength of the beams to be produced with conventional cement, 11 150x150x150 mm cube samples were produced. The produced samples were broken in various numbers on the 7th, 14th and 28th days and their compressive strength was measured. The view of the concrete during the test is presented in Figure 4.22 and the compressive strength results was given in the Table 4.8.



Figure 4.22 Compressive Strength Experiment of Concrete

Table 4.8 Compressive Strength Results of Concrete

Specimen	7. Day	14. Day	28. Day
1. Specimen	35.9 MPa	38.6 MPa	42.5 MPa
2. Specimen	36.0 MPa	41.9 MPa	42.2 MPa
3. Specimen		41.5 MPa	42.5 MPa
4. Specimen		40.4 MPa	43.2 MPa
5. Specimen			43.5 MPa

In addition to the compressive strength, 4 cylindrical samples with 200 mm length and 100 mm diameter and 4 cylindrical samples with 300 mm length and 150 mm diameter were produced from the same mixture in order to measure the splitting-tensile strength of the concrete. Splitting-tensile test was performed by applying vertical pressure loading to the plates placed below and above the cylindrical concrete samples placed between the tables of the press horizontally. By increasing the load, tensile stresses occur indirectly and slit along the axis of the sample.

**Figure 4.23** Splitting-Tensile Strength of Concrete

The formula given below is used for calculating splitting-tensile strength of the specimens:

$$\sigma = \frac{2P}{\pi \times L \times D}$$

where,

σ : Splitting-Tensile Strength (MPa)

P: Failure load of the cylinder sample (N),

L: Length of the cylinder sample (mm),

D: Diameter of the cylinder sample (mm).

The splitting-tensile strength results obtained after 28 days of ambient curing of the samples are presented in Table 4.9 and Table 4.10.

Table 4.9 Splitting-Tensile Strength Results of 1st Group Cylinders

Diameter: 150 mm	Specimen	Specimen	Specimen	Specimen
Length: 300 mm	1	2	3	4
Splitting-Tensile Strength	3.17 MPa	2.88 MPa	2.79 MPa	3.17 MPa



Figure 4.24 Crack formation in the cylinder after the test

Table 4.10 Splitting-Tensile Strength Results of 2nd Group Cylinders

Diameter: 150 mm	Specimen	Specimen	Specimen	Specimen
Length: 300 mm	1	2	3	4
Splitting-Tensile Strength	3.81 MPa	3.26 MPa	2.17 MPa	2.57 MPa



Figure 4.25 1st and 2nd group cylinders split into two after the experiment

Considering the compressive strengths of the produced concrete cubes, it reached 36 MPa pressure strength in 7 days, and maximum of 43.5 MPa compressive strength in 28 days. The results show that the concrete material has similar compressive strengths with the geopolymer mixtures developed within the scope of the thesis study. In addition, the produced cylinders were tested at 28 days to measure the splitting-tensile strength of the samples. According to the results obtained, the average splitting-tensile strength of the 1st group cylinders was 3 MPa, while the average splitting-tensile strength of the 2nd group cylinders was 2.95 MPa. According to the photo presented in Figure 4.25, it is observed that the samples are divided into two after the tensile test.

4.3.2. Shear-Critical Concrete Beam #1

In this part of the study, shear-critical concrete beam samples were produced and tested in order to make a comparison similar to the geopolymer beams. Shear-critical concrete beam #1 sample was produced by determining the stirrup distance as 200 mm for concrete beams designed as shear-critical. The a/d ratio of this beam was determined as 0.49. Before the concrete was poured, the reinforcement system weighed 4 kg, and the weight of the

geopolymer beam was 100 kg in the weighing made before the experiment. The volumes of all cast beams are constant and are 0.04125 m^3 . The density of this beam has been calculated as 2424.24 kg/m^3 . During the experiment, the first shear crack occurred in the beam under a 6.9 kN load on the back surface (Figure 4.26). Then, when the load of 7.2 kN is reached, the first bending crack was seen. The crack remained constant without any expansion, and the crack width was measured as 1 mm. In addition, the shear crack formed on the beam front surface under an 8.4 kN load has become prominent (Figure 4.27). As a result of the experiment, the width of the shear crack observed in the support on the back surface has reached 5 mm. Figure 4.29 also showed that the shear crack formed in the front surface support area as a result of the experiment.



Figure 4.26 The image of the Shear-Critical Concrete Beam #1 during the experiment

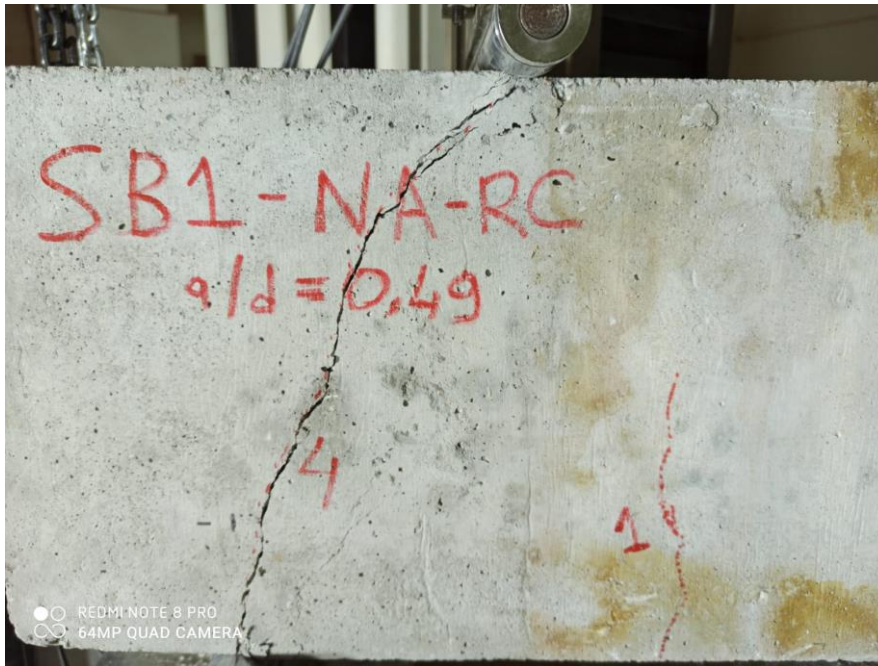


Figure 4.27 First shear crack formation in the support area of the specimen



Figure 4.28 Growth of shear crack in the support area of the specimen



Figure 4.29 Large shear crack at the back of the specimen after the test

Moment-curvature and load-deformation graphs of the Shear-Critical Concrete Beam #1 are presented in Figure 4.30 and Figure 4.31, respectively.

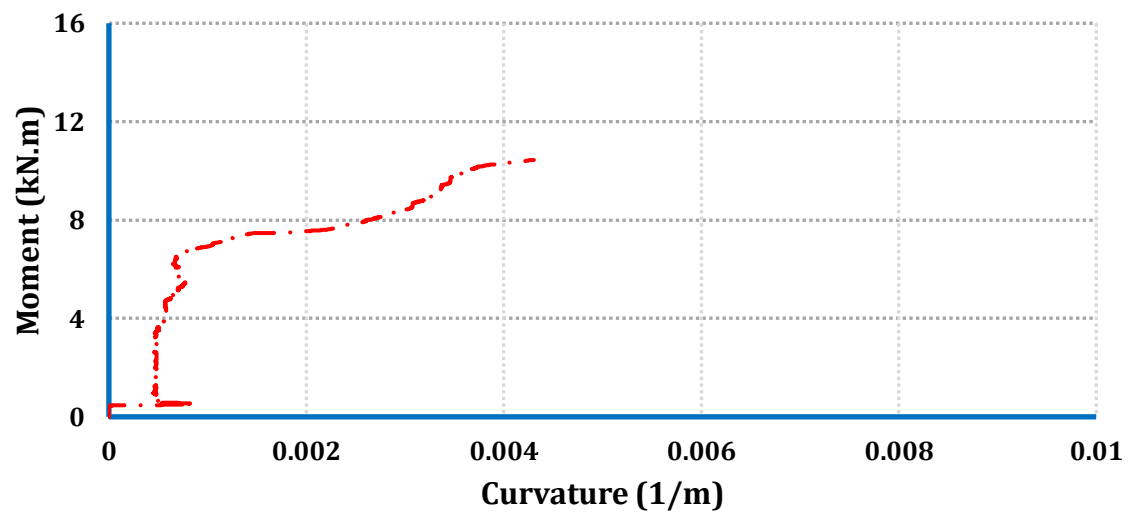


Figure 4.30 Moment-curvature results of the Shear-Critical Concrete Beam #1

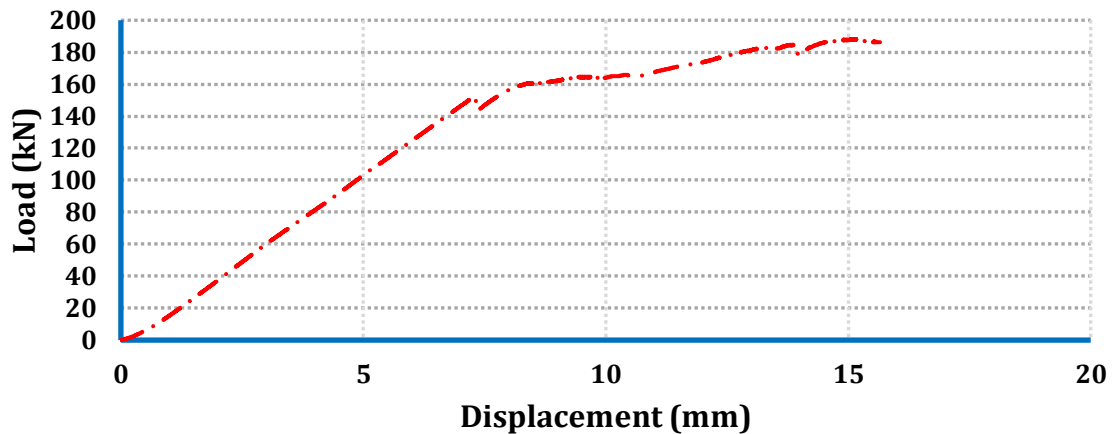


Figure 4.31 Load-displacement results of the Shear-Critical Concrete Beam #1

Considering the crack development, moment-curvature, and load-displacement graphs of Shear-Critical Concrete Beam #1 under load, it was seen that the concrete sample failed in shear. In addition, large cracks were seen in the shear span region of the samples as a result of the failure. When looking at the moment-curvature graph of Shear-Critical Concrete Beam # 1 presented in Figure 4.47, it was seen that it reached a maximum moment value of 10.44 kN.m, and the curvature value corresponding to this value was 0.004 1/m. Additionally, according to the load-displacement graph, it was seen that it has a maximum load-carrying capacity of 186 kN and a displacement behavior of approximately 15.6 mm.

4.3.3. Shear-Critical Concrete Beam #2

In the shear-critical concrete beam #2, the stirrup distance was determined as 200 mm, and the span distance was set as 245 mm in the setup. This value corresponds to an a/d ratio of 1.00. The reinforcement system before pouring concrete weighed 4 kg, and the weight of the reinforced concrete beam was 101 kg in the weighing made before the test. The volumes of all cast beams are constant and are 0.04125 m³. The density of this beam has been calculated as 2448,48 kg/m³. During the experiment, first bending cracks and then shear cracks were observed (Figure 4.32-4.35). At the point where the shear crack that occurred during the experiment cracked all of the concrete between the support and the loading system, the sample lost its full capacity.

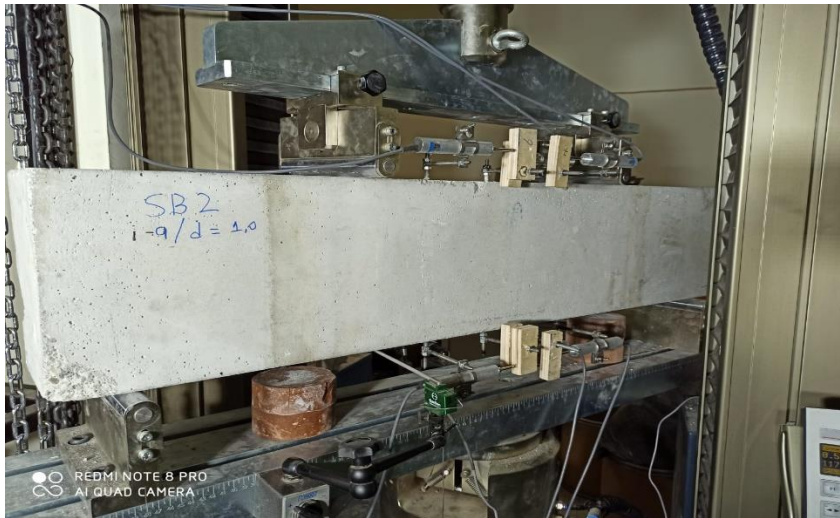


Figure 4.32 The image of the Shear-Critical Concrete Beam #2 during the experiment



Figure 4.33 Crack formation of the initial stage of the experiment

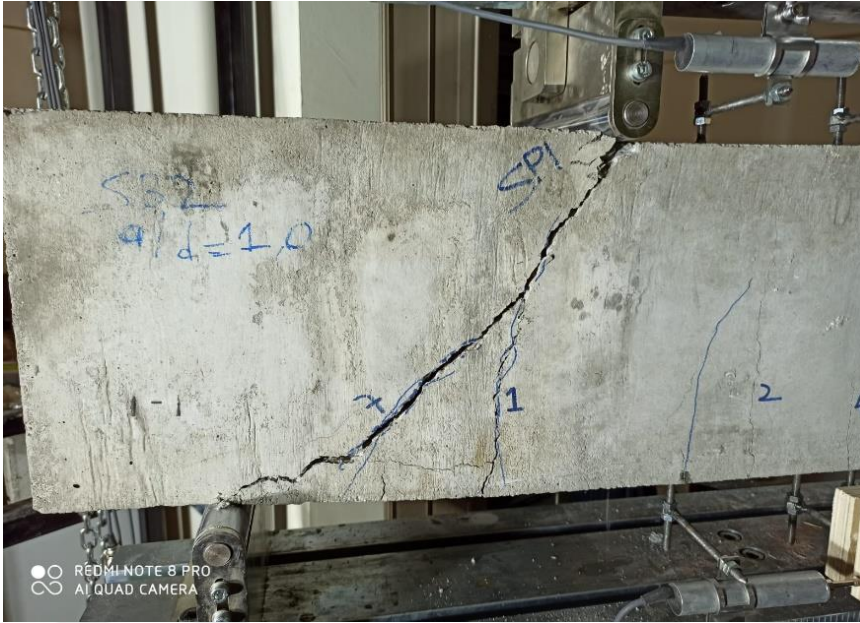


Figure 4.34 Shear crack formation during the experiment



Figure 4.35 Shear crack between the upper and lower support

Moment-curvature and load-deformation graphs of the Shear-Critical Concrete Beam #2 are presented in Figure 4.36 and Figure 4.37, respectively.

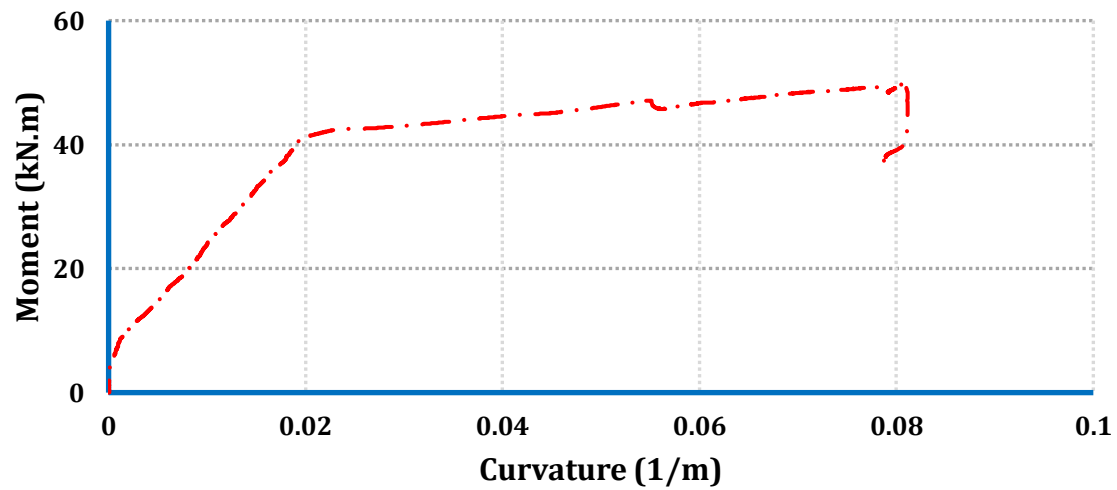


Figure 4.36 Moment-curvature results of the Shear-Critical Concrete Beam #2

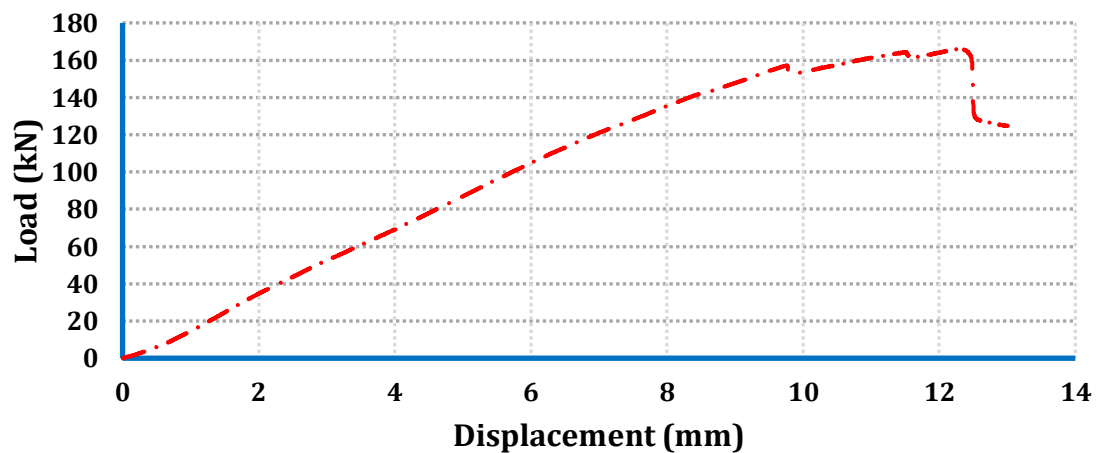


Figure 4.37 Load-displacement results of the Shear-Critical Concrete Beam #2

According to the results of Shear-critical concrete beam # 2, it was seen that concrete specimen failed in shear-dominated action. Additionally, it was seen that the formation of the cracks was shown between the load point and supports. Looking at the moment-curvature graph of the beam sample, it was observed that it reached a maximum moment value of 48,56 kN.m. This was considerably bigger than the ultimate moment of the concrete specimen, where the a/d ratio was 0.49. In addition, when the load-displacement graph of

the beam is examined, it is seen that it has a maximum load capacity of 162 kN and exhibited about 13 mm displacement.

4.3.4. Shear-Critical Concrete Beam #3

In the shear-critical concrete beam #3, the stirrup distance was determined as 200 mm, and the span distance was set as 405 mm in the setup. This value corresponds to an a/d ratio of 1.65. The reinforcement system before pouring concrete weighed 4 kg, and the weight of the reinforced geopolymer beam was 102 kg in the weighing made before the test. The volumes of all cast beams are constant and are 0.04125 m^3 . The density of this beam has been calculated as $2472,72 \text{ kg/m}^3$. Similar to Shear-critical concrete beam #2, first bending and then shear cracks were observed in this beam sample. The cracks observed from the beginning of the experiment to the sample collapse are presented in Figures 4.38-4.41.



Figure 4.38 The image of the Shear-Critical Concrete Beam #3 during the experiment

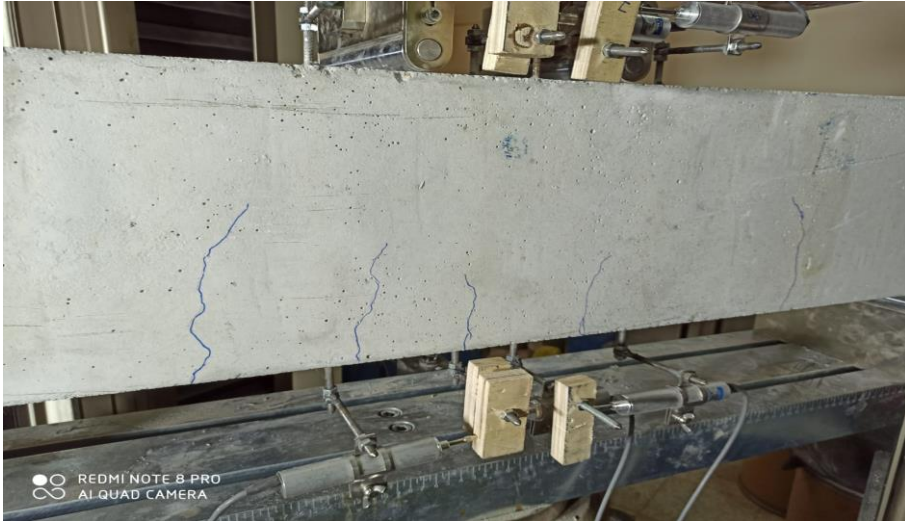


Figure 4.39 Crack formation under 4.6 kN load on the front surface

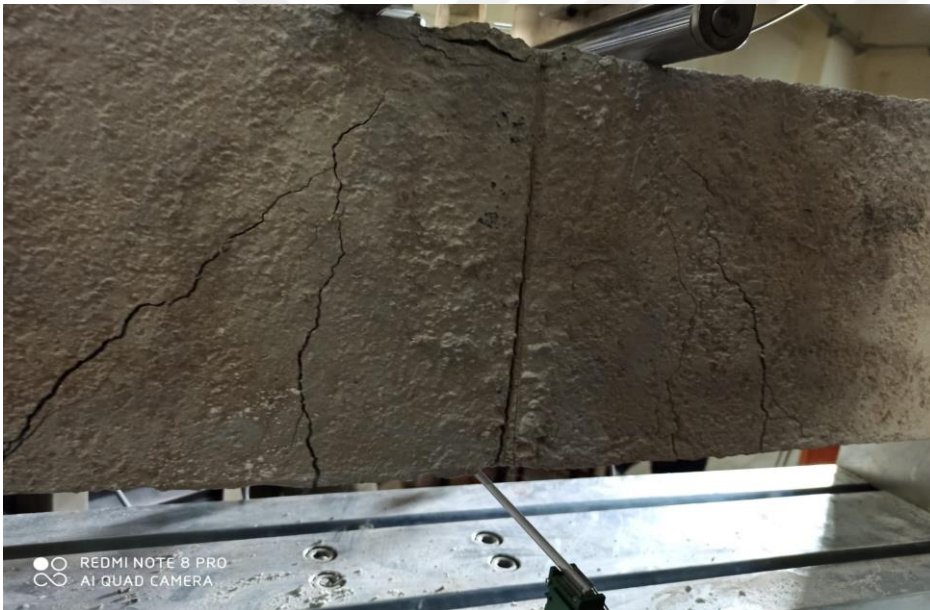


Figure 4.40 Shear and bending cracks seen on the back surface after test

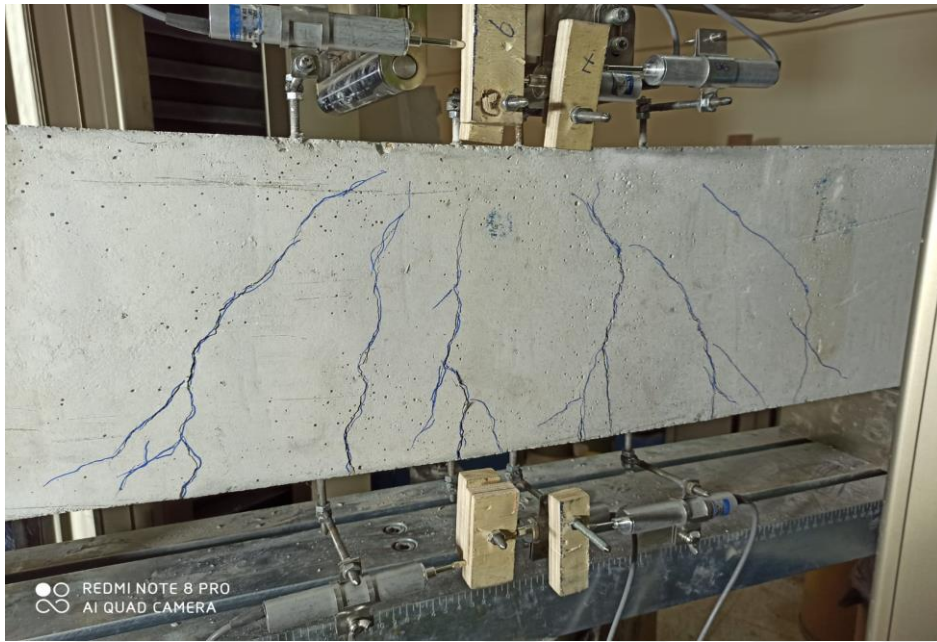


Figure 4.41 Shear and bending cracks seen on the front surface after the test

Moment-curvature and load-deformation graphs of the Shear-Critical Concrete Beam #3 are presented in Figure 4.42 and Figure 4.43, respectively.

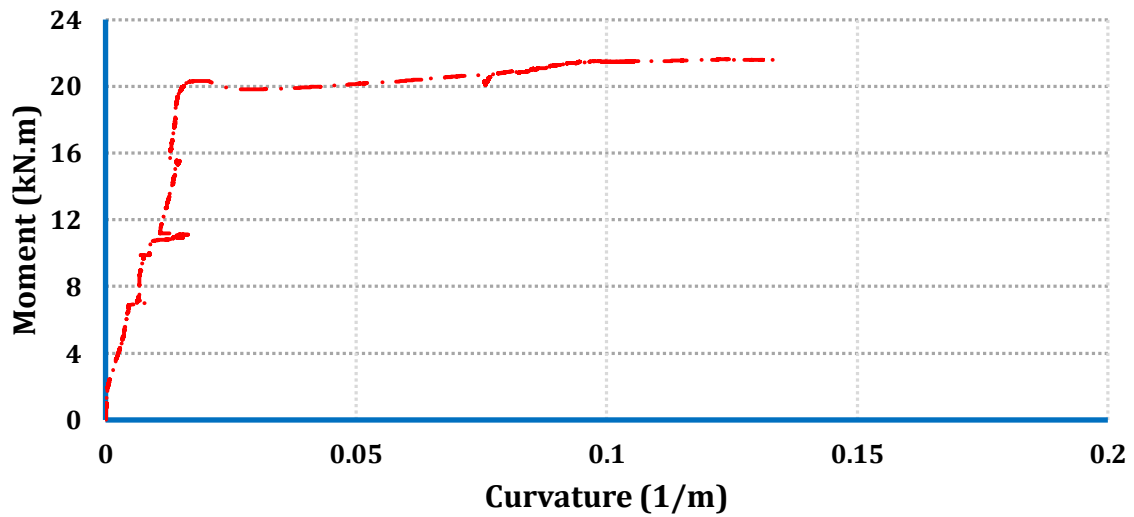


Figure 4.42 Moment-curvature results of the Shear-Critical Concrete Beam #3

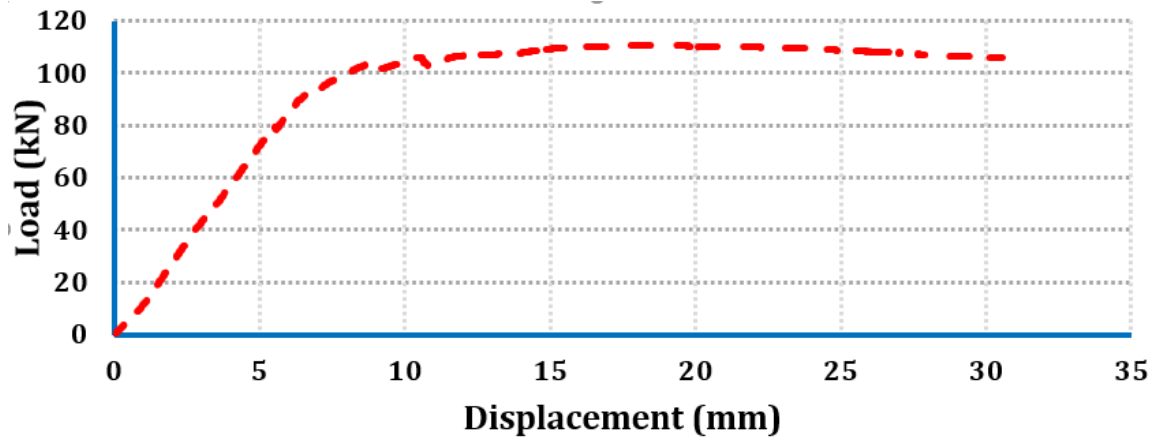


Figure 4.43 Load-displacement results of the Shear-Critical Concrete Beam #3

According to the results of Shear-Critical Concrete Beam #3, it was seen that concrete specimen failed in possible shear-flexure action. In addition, it has been observed that specimens failed by the mixed flexure and shear crack formation in shear span and constant moment span. According to the moment-curvature graph of the beam sample presented in Figure 4.42, it was observed that it reached a maximum moment value of 21.55 kN.m. This value was between the results of the two beams where the a/d ratio was 0.49 and 1.00. In addition, when the load-displacement graph of the beam is examined, it is seen that it has a maximum load capacity of 91.46 kN and exhibited about 14 mm displacement.

4.4. Comparison of Test Results of Geopolymer and Concrete Beams

4.4.1. Comparison of Shear-Critical Beams

In this part of the thesis, a comparison of test results of Shear-critical geopolymer and concrete beams designed with different a/d ratios are given. For this purpose, load-displacement results and moment-curvature of beams with the same a/d ratio are presented on the same graph. The moment-curvature graph of the shear-critical beams with an a/d ratio of 0.49 is given in Figure 4.44. Also, the load-displacement graph of the shear-critical beams with an a/d ratio of 0.49 is presented in Figure 4.45.

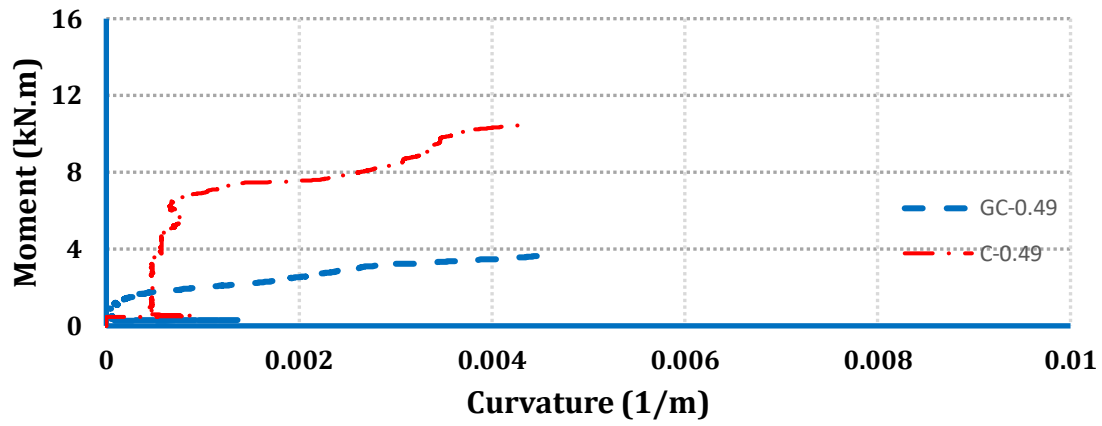


Figure 4.44 Moment-curvature comparison of Shear-critical beams with a/d ratio of 0.49

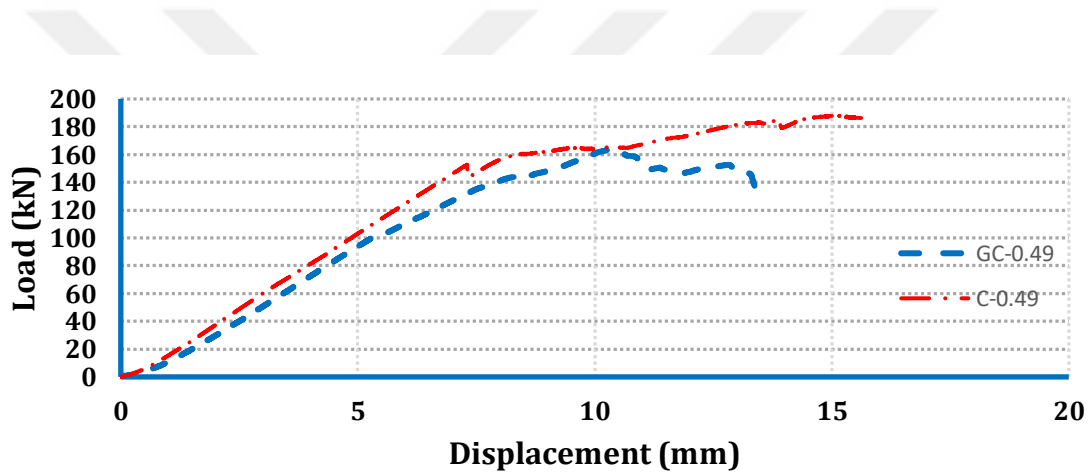


Figure 4.45 Load-displacement comparison of Shear-critical beams with a/d ratio of 0.49

The moment-curvature graph of the shear-critical beams with a 1.00 a/d ratio is given in Figure 4.46. Also, the load-displacement graph of the shear-critical beams with a 1.00 a/d ratio is presented in Figure 4.47.

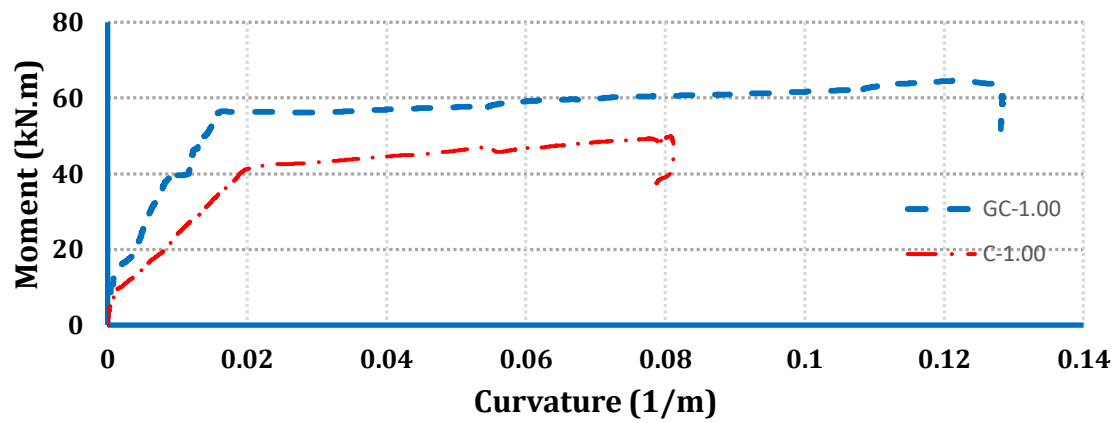


Figure 4.46 Moment-curvature comparison of Shear-critical beams with a/d ratio of 1.00

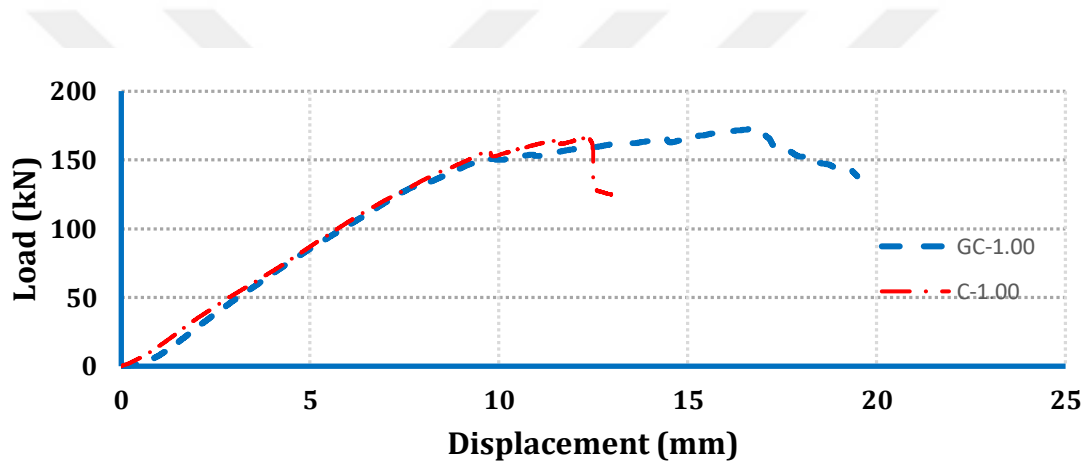


Figure 4.47 Load-displacement comparison of Shear-critical beams with a/d ratio of 1.00

The moment-curvature graph of the shear-critical beams with a 1.65 a/d ratio is presented in Figure 4.48. Also, the load-displacement graph of the shear-critical beams with an a/d ratio of 1.65 is presented in Figure 4.49.

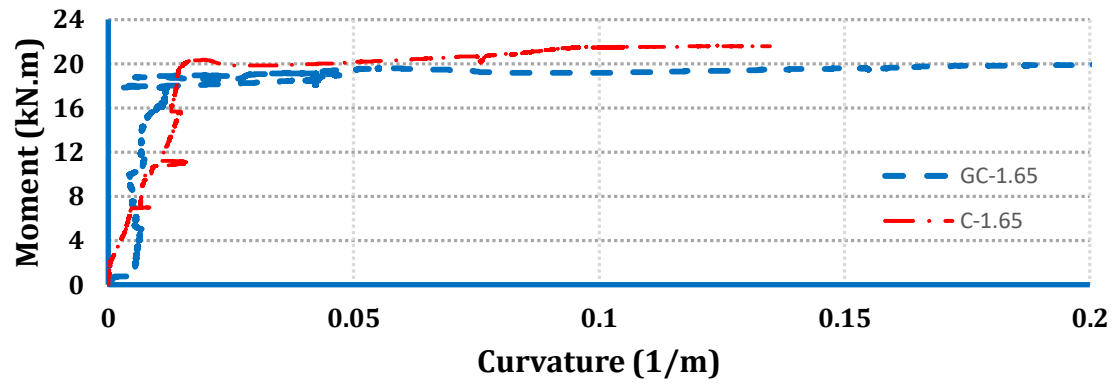


Figure 4.48 Moment-curvature comparison of Shear-critical beams with a/d ratio of 1.65

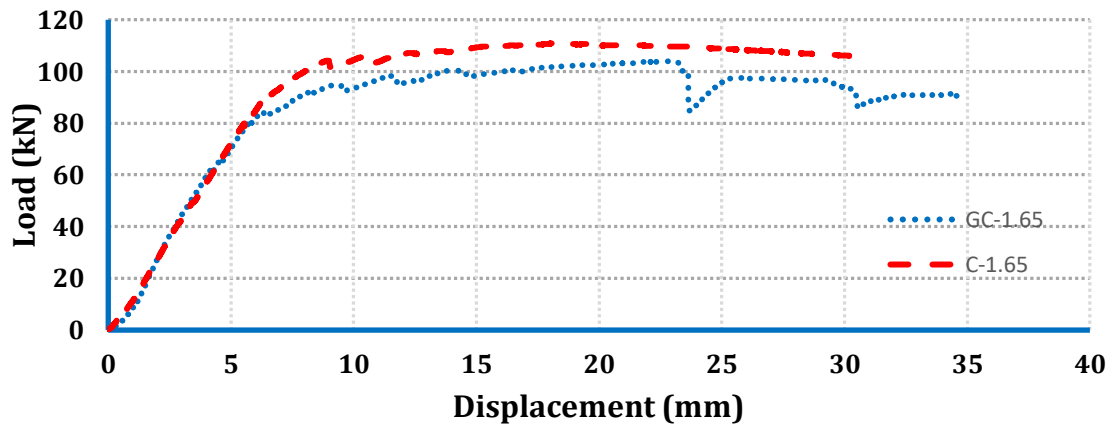


Figure 4.49 Load-displacement comparison of Shear-critical beams with a/d ratio of 1.65

The rigidity and normalized energy capacity of Shear-critical concrete and geopolymer beams with a/d ratios of 0.49, 1.00 and 1.65 are presented in Table 4.11.

Table 4.11 Rigidity and Normalized Energy Capacity of Shear-critical beams

Concrete Beam			Geopolymer Beam	
a/d	Rigidity	Normalized Energy Capacity	Rigidity	Normalized Energy Capacity
0.49	33210.23	0.185	30375.85	0.138
1.00	20283.56	1.299	20199.36	0.390
1.65	19290.32	0.0019	16093.57	3.257

According to the moment-curvature result presented in Figure 4.44, it was seen that the moment values of the concrete beam were clearly greater than the geopolymer beam. Although both beams reached similar curvature values according to the results, it was observed that the concrete beam was 2.5 times more than the geopolymer beam as the moment value. Looking at the moment-curvature graph with a/d ratio of 1.00 presented in Figure 4.46, it was seen that this time the geopolymer beam had reached a higher value than the concrete beam in terms of both moment and curvature values. In addition, the difference in moment-curvature results between these two beams was less than the difference observed at 0.49 a/d. According to the results presented in Figure 4.48, within the scope of moment-curvature values of Shear-critical beams, it was observed that concrete and geopolymer beams exhibited very close results to each other. This shows that the low a/d ratio is quite effective in terms of moment-curvature values, but as the a/d ratio is increased, the building material used exhibits similar results even though it is different.

Considering the load and displacement results of the Shear-critical beams, it was seen that the concrete beam has a higher load and displacement value. This is related to the fact that concrete beams show a higher load-carrying capacity at low a/d ratio, since the concrete material exhibits slightly higher compressive strength than the geopolymer. According to the results presented in Figure 4.47, where the a/d ratio is 1.00, it was seen that the concrete and geopolymer beam have reached similar maximum load capacity, while the geopolymer beam has a more ductile behavior. Finally, in the comparison of the Shear-critical beam, it

was seen that the concrete and geopolymer beam behave very similarly according to the results presented in Figure 4.49 with an a/d ratio of 1.65. Similar to the moment-curvature values, the behavior of both the geopolymer beam and the concrete beam under load was similar with the increase in the a/d ratio. This proves that materials produced as Shear-critical and with similar compressive strength show similar structural properties.

At last, when looking at the rigidity and normalized energy capacity values of Shear-critical beams presented in Table 4.11, concrete beams exhibited slightly higher results than geopolymer beams in terms of rigidity value. The beams showed similar results at three different a/d ratios in terms of normalized energy values.



5. CONCLUSION

- Within the scope of this thesis, the new generation eco-friendly geopolymer beams were produced using construction demolition waste (CDW)-based materials such as roof tile (RT), red clay brick (RCB), hollow brick (HB), glass waste (GW) and concrete waste (CW) and structural tests were carried out. After the determination of the geopolymer and Portland cement concrete mixtures, the beam production and structural tests were started as the final aim of the study. In this context, the beam design was made in two different ways as shear-critical beams. Shear-critical beams were produced by determining the stirrup distance as 200 mm. Three different a/d ratios of 0.49, 1.00 and 1.65 were selected for each beam design. To compare structural property of geopolymer beams, traditional Portland cement beams were produced and the same tests were carried out. As a result of the studies carried out for this purpose, the following results have been obtained:
- Materials obtained from construction and demolition wastes were brought to approximately average cement fineness as a result of direct crushing and grinding processes without any treatment. The geopolymer paste production was carried out using sodium hydroxide as an alkaline activator and using these aluminosilicate-based materials in single and five-point combinations. As a result of single uses, the roof tile exhibited 68 MPa compressive strength after its reaction with 15 moles of sodium hydroxide and after 48 hours curing at 115 °C. In the mixture where all construction and demolition wastes are used together, 57 MPa compressive strength was reached.
- By the successful development of geopolymer paste with oven curing, works on the geopolymer concrete production were started. In this context, various geopolymer concrete mix designs were made by substituting fly ash and slag to the construction and demolition waste materials and adding alkali activators such as sodium silicate and calcium hydroxide in addition to sodium hydroxide. As a result of the designs made, the maximum compressive strength of 34.1 MPa was reached after 28 days of ambient curing. According to the findings, it has been observed that the substitution

of 15% blast furnace slag and 5% fly ash significantly increases the compressive strength and workability. In addition, the use of sodium silicate and calcium hydroxide as alkali activators also played a major role in strength development for ambient curing.

- After the evaluation of the geopolymer concrete mixture designs, the mixture with the highest compressive strength was selected and Portland cement concrete with similar compressive strength was produced. Before producing beams with these two different materials, cubic and cylindrical samples were produced. When examining the results, the ultimate compressive strength of the geopolymer concrete was 32.1 MPa, while the splitting tensile strength was maximum of 2.41 MPa. The average compressive strength of Portland cement concrete for 28 days of ambient curing was 43 MPa, while the tensile strength in splitting was 2.97 MPa.
- Shear-critical beams designed with a/d ratio of 0.49 failed in shear regardless of the building material. In beam specimens under load, crack expansion in shear span was determined. While a significant difference was observed in moment-curvature results between concrete and geopolymer beam samples, the load-carrying capacity and ductility of the concrete beam were higher in load-displacement results because of the higher compressive strength of concrete sample.
- Shear-critical beams designed with a/d ratio of 1.00 failed in shear-dominant action. During the test in beam samples, failure occurred due to crack formation between the support and the middle span. In addition, these beam samples showed a higher moment-curvature value. According to the load-carrying capacity results, in beams with similar load-carrying value, the geopolymer beam was able to displace 19.5 mm, while the concrete beam was able to reach a maximum displacement value of 12.81 mm.
- Shear-critical beams designed with a/d ratio of 1.65 failed in mixed and flexure behavior. During the test in beam samples, two types of crack formation were observed; inclined shear cracks in the support area and vertical flexure cracks in the constant moment span. However, geopolymer and concrete beams showed closer

moment-curvature and load-displacement behaviors than other a/d ratios. Under the four-point bending test, the concrete beam showed a maximum displacement of 30.52 mm, while the geopolymer beam showed a displacement of about 35 mm.

- According to the findings obtained as a result of the study, it was seen that geopolymer concretes with similar compressive strengths compared to Portland cement concrete behave very close to each other in terms of structural performance. While the produced beam samples were found to be comparable in terms of moment-curvature and load-displacement properties, crack patterns and dent modes were found to have very similar behavior. With this result, it seems quite possible that environmentally friendly and sustainable geopolymer concretes produced by the use of construction and demolition wastes will enter our lives with the structural use of them in the future, and thus the environmental damage of Portland cement will be minimized.

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