MECHANICAL PERFORMANCE OF BARITE COLEMANITE CONCRETE USING DOE-BASED FORMULATION FOR RADIATION SHIELDING

Safwan Shalbi[1], Muhammad Aliff Ashraff Rosdi[1], Norazlianie Sazali[1] Faridah Mohamad Idris[2], Asyraf Arif Bin Abu Bakar[2]

[1]*Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA)*
[2]*Malaysian Nuclear Agency, Bangi, 43000 Kajang, Selangor, Malaysia*

e-mail: safwanshalbi@gmail.com

ABSTRACT

This study focuses on the preparation and evaluation of barite colemanite concrete samples for radiation shielding applications, with a target compressive strength of 40 MPa. Various concrete mixtures were formulated using DOE method, resulting in four distinct samples labelled A, B, C, and D. The research emphasizes the importance of achieving Grade 40 concrete properties suitable for components in Boron Neutron Capture Therapy (BNCT) at nuclear reactors. Sample A adhered to the DOE-specified ratio, featuring colemanite as fine aggregates, while samples B, C, and D incorporated colemanite as a filler. The adjustment of water and colemanite content was crucial, with reduced water content in samples B, C, and D to achieve the desired strength without compromising workability. All samples exceeded the target density of 2375 kg/m3, with sample C achieving the highest density of 2904 kg/m3, emphasizing the impact of water and colemanite proportions on density. The ultrasonic pulse velocity (UPV) test indicated that the barite colemanite concrete possessed good quality and suitability for shielding applications. Workability, assessed through the slump test, indicated that all samples, except sample B, exhibited good workability within the Grade 40 range. The inverse relationship between slump and density highlighted the importance of density in workability. Compressive strength testing revealed that mixture D surpassed the Grade 40 threshold, exhibiting a remarkable 56% increase in load-bearing capacity between 7 and 14 days of curing. In contrast, mixtures A, B, and C remained below the desired strength.

ABSTRAK

Kajian ini memberi tumpuan kepada penyediaan dan penilaian sampel konkrit barit colemanite untuk aplikasi perisai sinaran, dengan kekuatan mampatan sasaran 40 MPa. Pelbagai campuran konkrit telah dirumus menggunakan kaedah DOE, menghasilkan empat sampel berbeza yang dilabelkan A, B, C, dan D. Penyelidikan ini menekankan kepentingan untuk mencapai sifat konkrit Gred 40 yang sesuai untuk komponen dalam Terapi Tangkapan Neutron Boron (BNCT) di reaktor nuklear. Sampel A mematuhi nisbah yang ditentukan DOE, menampilkan colemanite sebagai agregat halus, manakala sampel B, C, dan D menggabungkan colemanite sebagai pengisi. Pelarasan kandungan air dan kolemanit adalah penting, dengan pengurangan kandungan air dalam sampel B, C, dan D untuk mencapai kekuatan yang diingini tanpa menjejaskan kebolehkerjaan. Semua sampel melebihi ketumpatan sasaran 2375 kg/m3, dengan sampel C mencapai ketumpatan tertinggi 2904 kg/m3, menekankan kesan air dan perkadaran kolemanit pada ketumpatan. Ujian halaju nadi ultrasonik (UPV) menunjukkan bahawa konkrit barit colemanite mempunyai kualiti yang baik dan kesesuaian untuk aplikasi perisai. Kebolehkerjaan, yang *dinilai melalui ujian kemerosotan, menunjukkan bahawa semua sampel, kecuali sampel B, mempamerkan kebolehkerjaan yang baik dalam julat Gred 40. Hubungan songsang antara kemerosotan dan ketumpatan menyerlahkan kepentingan ketumpatan dalam kebolehkerjaan. Ujian kekuatan mampatan mendedahkan bahawa campuran D melepasi ambang Gred 40, menunjukkan peningkatan 56% yang luar biasa dalam kapasiti galas beban antara 7 dan 14 hari pengawetan. Sebaliknya, campuran A, B, dan C kekal di bawah kekuatan yang dikehendaki.*

Keywords: Barite Colemanite Concrete, Radiation Shielding, Boron Neutron Capture Therapy (BNCT)

INTRODUCTION

In the realm of radiation protection, concrete stands as a stalwart shield against harmful ionizing radiation. This study delves into the creation of a specialized concrete mix called barite colemanite concrete, designed to meet the rigorous Grade 40 strength standards essential for shielding in applications like Boron Neutron Capture Therapy (BNCT) at nuclear research reactors. DOE method was implemented to systematically optimize the composition of barite colemanite concrete. Through a series of tests, a lot of factors need to be considered such as water content, colemanite as a filler, and the use of plasticizers to achieve a blend that not only meets the Grade 40 strength criteria but also boasts excellent workability and density. The findings have the potential to revolutionize radiation shielding by offering a concrete solution that combines robust protection with ease of use. As the demand for effective shielding materials continues to rise across industries, our research contributes to safer and more efficient radiation protection methods.

MATERIALS AND METHOD

Preparation of Barite Colemanite Concrete Samples

The procedure for conducting the sample is identical to that for other types of concrete mixing tests. All concrete materials were weighed before being mixed in the rotary cement concrete mixer. To determine if the desired slump had been achieved, a slump test was performed in accordance with ASTM C143 (ASTM, 2022). Next, the concrete mixture was poured into a 15 cm x 15 cm mold and compacted using a vibrator. After 24 hours, the concrete was removed from the mold and left to cure in a water tank for a total of 28 days.

In this study, various concrete mixtures were formulated using the DOE method, with a target mean strength of 40 MPa for all samples of barite colemanite concrete. The complete formulation for barite colemanite concrete based on the DOE method. According to the calculations and tables from the DOE method, the standard ratio for a 40 MPa concrete mix was 1.5:0.6:2.1:3.8 for cement, water, fine aggregate, and coarse aggregate, respectively. In sample A, colemanite served as the fine aggregate, while in samples B, C, and D, it functioned as a filler in the barite colemanite concrete. A total of 23 formulations were generated using the DOE method. However, most of them disintegrated during the curing process, leaving only 4 samples that could be utilized in this research, as indicated in Table 1.

Table 1 The DOE method mixed concrete formulation

	iMixture (%)			
Material	**A**	**B**	**C**	**D**
Cement	12.39	i18.74	i18.74	i20.18
Water	i8.17	i7.5	i6.88	i4.65
Sand	i20.28	i25	i25	i24.71
Colemanite	i11.27	i1.25	i1.88	i1.85
Barite	i45.07	i46.5	i46.5	i46.95
Plasticizer	i2.82	i1	i1	i1.65

The research presented in Table 1 aimed to develop a Grade 40 barite colemanite mixture intended for use in radiation shielding applications. Four distinct mixtures, denoted as A, B, C, and D, were tested with a target compressive strength of 40 MPa serving as the benchmark. This choice of 40 MPa as the target compressive strength aligns with the definition of Grade 40 concrete as indicated by Saravanan & Jagadeesh[1]. According to Saravanan & Jagadeesh (2015), concrete with a compressive strength of 40 MPa is considered high strength and suitable for structural and load-bearing applications such as foundations and beams. The selection of 40 MPa as the target compressive strength in this research was driven by the need to ensure that the final concrete mixture would possess sufficient strength for radiation shielding applications, meeting Grade 40 mechanical properties for components used in Boron Neutron Capture Therapy (BNCT) at nuclear reactors.

Sample A adhered to the same ratio as the guideline, with colemanite used as fine aggregates at a ratio of 0.48 colemanite to 0.52 sand. Sample A featured the highest colemanite content among all the samples and was formulated strictly according to the specified proportions. In contrast, samples B, C, and D were modified to determine the most suitable proportion, taking into account the role of colemanite as a filler.

The adjustment of water and colemanite content was critical in this research, as the goal was to achieve a Grade 40 barite colemanite mixture with minimal mechanical strength. Given colemanite's role as a filler, the water content was reduced from 7.5% in sample B, 6.2% in sample C, and 5.5% in sample D, respectively. As highlighted by Awoyera et al.[2], the filler content in concrete should be less than 10% of the water content to distinguish between fine aggregates and fillers. The reduction in water content for sample B was less than 1%, 1.3% for sample C, and 2% for sample D compared to the water content in sample A. This reduction in water content, though significant, did not match the reduction in colemanite content because water played a crucial role in the hydration process of barite colemanite concrete [3]

In the case of sample D, the quantities of plasticizer and cement were increased to investigate the impact of barite colemanite on mechanical strength. According to Nagrockiene, Pundienė, & Kicaite [4] pasticizers can enhance the bonding structure and accelerate the hydration process of concrete. All samples underwent a 28-day curing process to ensure that the concrete had reached its ultimate strength and properties. As asserted by Mohammad Abdul Kreem [5], the curing process is a vital step in concrete production, involving the maintenance of adequate moisture and temperature conditions to allow cement to hydrate and develop the desired properties. A standard curing period for concrete is typically 28 days, ensuring that the concrete achieves its maximum strength and properties [5]

The research in Table 1 aimed to develop Grade 40 barite colemanite mixtures for radiation shielding. Four variants, labeled A, B, C, and D, targeted a 40 MPa compressive strength, consistent with Grade 40 concrete defined by Saravanan & Jagadeesh (2015). This strength level suits structural applications like foundations and beams. The selection of 40 MPa aligns with the requirements for components in Boron Neutron Capture Therapy (BNCT) at nuclear reactors.

Barite Colemanite Concrete Samples Test

Slump testing was conducted on the concrete mixture at various stages of the sample preparation process to assess the consistency of the newly formulated concrete. Subsequently, the mechanical properties of the barite colemanite concrete samples were assessed following a 28-day curing period, as outlined by Mohammad Abdul Kreem in 2012 [5].

Barite Colemanite Concrete Testing

To attain a Grade 40 concrete, it is necessary to establish a desired density for the samples, and the observed density is then measured after a 28-day period. The reference density for this concrete, approximately 2375 kg/m3, is derived from Grade 40,[6]. This designated density is associated with the concrete's mechanical strength, serving as an indicator for the samples to reach the intended mechanical strength. Figure 1 illustrates the achieved density compared to the desired target density for all the samples.

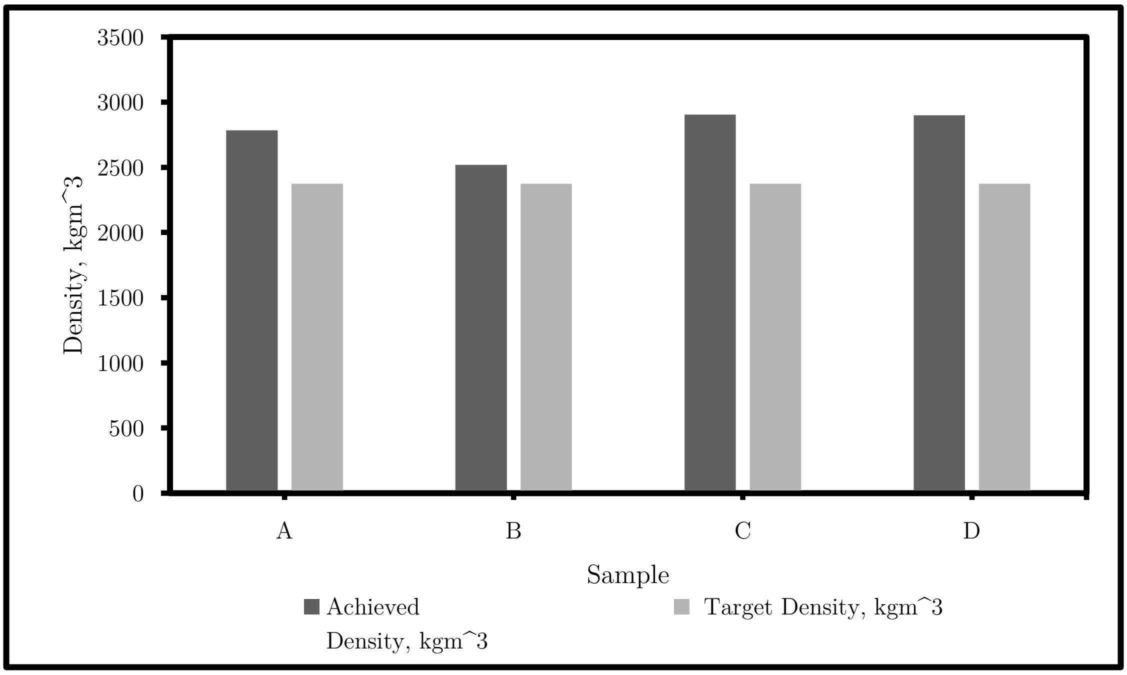

Figure 1 The graphical result of achieved density and target density for all samples

Figure 1 visually demonstrates that all the samples have successfully exceeded the designated target density of 2375 kg/m3, despite variations in their compositions. Notably, the data reveals that sample C exhibits the highest density among all mixtures, measuring at 2904 kg/m3, which is a remarkable 22% higher than the target density. Interestingly, even though mixture C shares an identical percentage of cement, plasticizer, barite, and sand with mixture B, differences in water and colemanite proportions yield a significant disparity in achieved density. This observation underscores the profound impact of water and colemanite percentages on concrete density, as suggested by Oto et al. [7]

Furthermore, while mixture A contains the highest colemanite content, mainly attributed to colemanite serving as a fine aggregate, it achieved a density 10.56% higher than mixture B. This outcome can be attributed to the substantial 18.2% increase in plasticizer content in mixture A compared to mixture B. The inclusion of a plasticizer in the concrete mixture serves to reduce water and cement content while enhancing workability and imparting early-age strength, as highlighted by Khan and Ali [8]. Therefore, despite the elevated colemanite content, mixture A demonstrates superior density performance compared to mixture B. In sum, all sample compositions surpass the target density, and these results underscore the influence of colemanite and plasticizer on achieved density.

RESULT AND DISCUSSION

Mechanical Properties of Barite Colemanite Concrete

The mechanical characteristics of the concrete samples containing barite and colemanite were assessed through three standard testing methods in accordance with ASTM guidelines. As indicated in Table 2, the average pulse velocity for the designed mixture of barite and colemanite concrete was recorded at 3.77 km/s. This value suggests that the quality of the concrete, although generally good, may exhibit some minor porosity, as per the standards referenced [9]. It's worth noting that the results of the ultrasonic pulse velocity (UPV) test can be influenced by factors such as the type of aggregate, stress conditions, and reinforcement. The use of composite concrete, such as that containing barite and colemanite, is expected to introduce porosity due to the presence of different aggregate types compared to normal concrete.

Furthermore, UPV test results showed a gradual increase with the rise in aggregate content. The remarks made about UPV testing results depend on the intended concrete application, as discussed by Biswas, Rai, and Samui [10]. For instance, a velocity exceeding 4.00 km/s is necessary for excellent concrete quality in applications like high-rise buildings, bridges, and foundations [11]. Consequently, with a velocity exceeding 3.5 km/s, the barite colemanite concrete can be considered of good quality and suitable for applications like shielding, as there are no observable cracks or defects in the samples.

Figure 2 graphically illustrates the relationship between pulse velocity and density for all the samples. The graph clearly demonstrates that densities of 2600 kg/m3 and above correspond to velocities exceeding 3.5 km/s. Notably, mixture A exhibits the lowest velocity among all the samples, while mixture B is the only sample that achieved a velocity exceeding 4.00 km/s in the UPV test. This difference can be attributed to the higher colemanite content in mixture A, which results in an elevated boron element concentration. This affects the concrete's hydration process, weakens the bonding structure, reduces homogeneity, and increases porosity compared to other samples [12].

According to Biswas, Rai, and Samui [10] there is a direct proportional relationship between UPV and density, but within the range of 1850 to 2450 kg/m3 of density. However, the graph in Figure 2 clearly demonstrates that densities exceeding 2600 kg/m3 from this research sample do not exhibit a direct proportional relationship with UPV. This variance in UPV results can be attributed to the use of composite concrete, such as barite colemanite concrete, which produces higher density and leads to different UPV outcomes due to variations in aggregate type and element content.

Table 2 Result of barite colemanite samples for slump test, pulse velocity and compressive strength test

Sample	Slump Test (mm)	Pulse velocity(km/s)	Compressive Strength Test (N/mm^2)
A	33	3.62	33
B	63	4.11	32
C	40	3.89	32
D	36	3.76	42

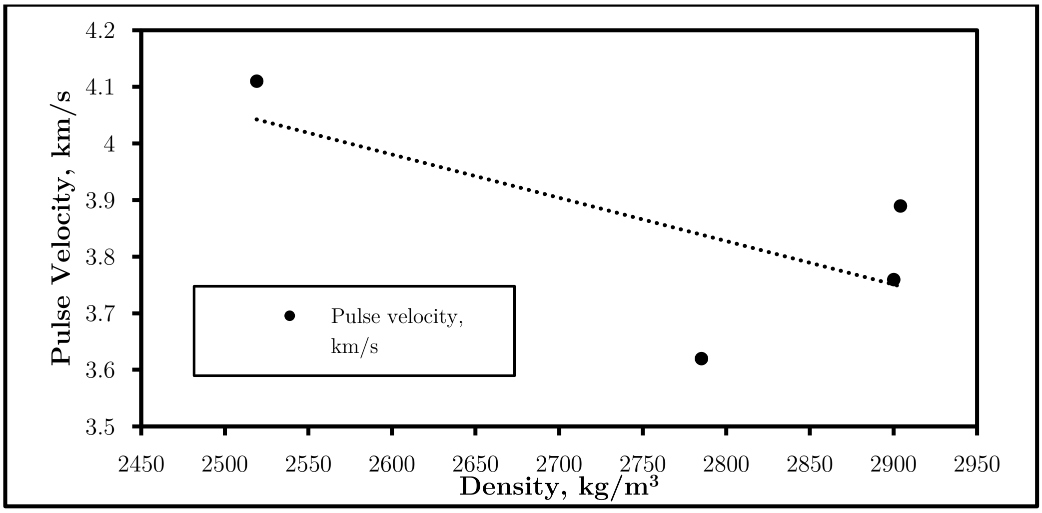

Figure 1 The relationship between pulse velocity against density

To evaluate the workability of barite colemanite concrete, the slump test was conducted for each sample prior to pouring the mixture into the cube mold. In the nuclear industry, certain shielding applications necessitate unique designs such as zigzag and honeycomb configurations to effectively contain radiation and prevent any leakage. Consequently, having good workability is essential to ensure that the shielding can be precisely molded according to these specific designs. On the contrary, poor workability of the mixed concrete results in a rigid consistency that is unsuitable for effective shielding purposes, as noted by Roslan et al. [13]. To achieve Grade 40, The standard slump test for the produced concrete should ideally yield results between 30mm and 60mm. It's worth noting that all the samples, except for sample B, fall within this range, indicating good workability and suitability for shielding design. Sample B exhibited a slightly higher value, exceeding the maximum slump by only 3 mm.

As illustrated in Figure 3, there is an inverse relationship between slump and density. This means that as the density increases, the slump decreases, reflecting the higher workability inherent in the concrete structure. Additionally, density plays a critical role in determining the excellent workability of mixed concrete, particularly for shielding applications, as emphasized by Roslan et al. [13].

Figure 3 reveals that three mixture samples, namely samples B, C, and D, are deemed suitable for use as barite colemanite concrete. These samples meet the workability criteria and exhibit the desired density for effective shielding applications.

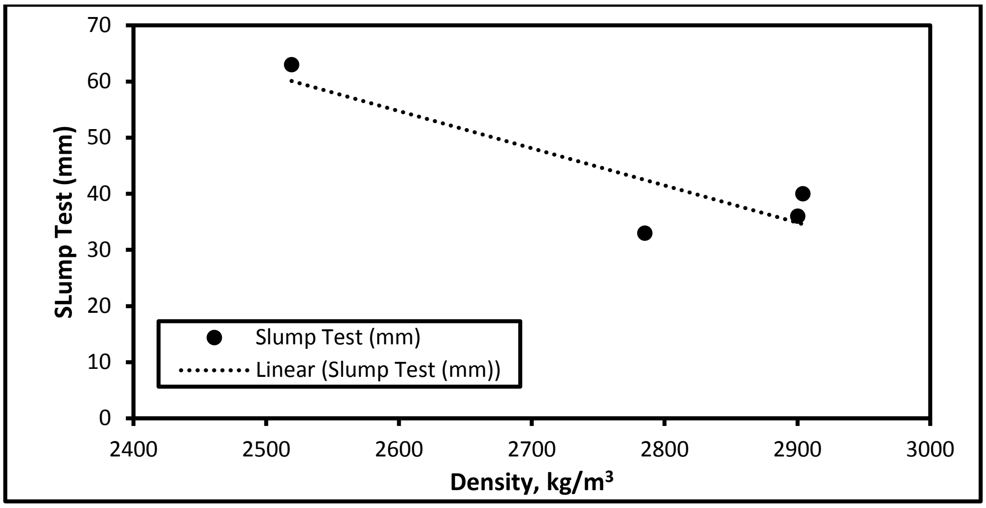

Figure 2 The relationship between slump (mm) against density

In order to determine the most suitable mixture formulation of barite colemanite for BNCT (Boron Neutron Capture Therapy) shielding, the compressive strength test emerged as the pivotal assessment method, particularly with regard to mechanical properties, as underscored by Biswas, Rai, and Samui [10].

As outlined in Table 2, mixture D exhibited a compressive strength of 42 N/mm2, surpassing the 40 N/mm2 threshold required for Grade 40 concrete. In contrast, the other mixtures yielded compressive strengths below 40 N/mm2. The measurement of compressive strength was conducted at intervals of 7, 14, and 28 days, as detailed in Table 3. This data is crucial in establishing the concrete's long-term performance and suitability for BNCT shielding applications.

Table 3 The measurement of compressive strength on 7, 14 and 28 days

Mixtures	Averaged Density, kg/m3	Maximum Load,kN (7days)	Maximum Load,kN (14days)	Maximum Load,kN (28days)	Compressive Strength (N/mm^2)
A	2785	471	480	520	33
B	2519	296	494	475	32
C	2904	300	429	480	32
D	2900	593	926	967	42

Table 3 illustrates that all the mixtures have exhibited an increase in their compressive strength as the curing period progressed. This improvement in strength can be attributed to the curing period's role in enhancing concrete strength development by regulating the moisture content within the concrete mixtures, as explained by Khatib and Mangat [14].

Notably, mixture D has shown a remarkable 56% increase in load-bearing capacity, as indicated by the percentage difference between the maximum loads measured at 7 and 14 days. On the other hand, mixtures A, B, and C also exhibited an increase in load capacity over time. However, their mechanical strength remained below the crucial threshold of 40MPa, making them unsuitable for use as barite colemanite formulations for shielding the BNCT research facility.

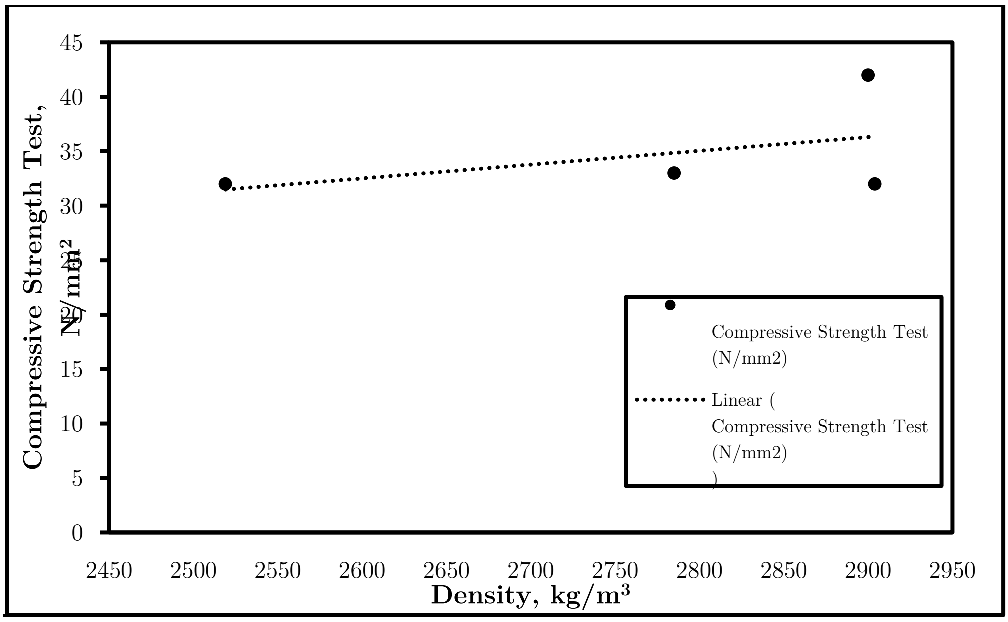

Figure 4 The accord between compressive strength against density

In summary, the formulation of concrete mixtures using the DOE method, with colemanite as a filler and reduced water content, has yielded the highest compressive strength. Among the various mixtures tested, mixture D, with a composition of 1.85% colemanite, 46.95% barite, and 4.65% water, successfully achieved a mechanical strength equivalent to Grade 40 concrete, surpassing the performance of other mixtures. The use of colemanite as a filler in combination with reduced water content has had a positive impact on the bonding structure of barite colemanite concrete, resulting in enhanced mechanical strength compared to colemanite as fine aggregates. Additionally, the achieved density, slump test, and ultrasonic pulse velocity (UPV) results have demonstrated the superior capabilities of mixture D compared to mixture A.

It's important to note that the use of more than 10% colemanite as a fine aggregate in mixture A, as determined by the DOE method, led to higher compressive strength compared to barite colemanite concrete produced in previous research by Mesbahi [15]. Mesbahi's research using the American Concrete Institute (ACI) method with 10% colemanite as fine aggregate achieved a compressive strength of only 24 MPa, which is 9 MPa lower than mixture A in this study.

CONCLUSION

In conclusion, this study has revealed that the key to achieving high compressive strength in concrete lies not solely in density but in the material proportions and conditions. The critical factors for formulating concrete with excellent mechanical properties include low water content, the use of additives such as a high plasticizer, and the incorporation of colemanite as a filler. As a result of this investigation, only mixture D of barite colemanite concrete has met or exceeded the minimum standards for mechanical attributes, encompassing concrete quality, workability, density, and strength.

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REFERENCES

[1] S.S Saravanan, P.Jagadesh (2015). Assessment of compressive strength of M40 concrete with manufactured sand-an application based concrete mix

[2] Awoyera, P. O., Adesina, A., & Gobinath, R. (2019). Role of recycling fine materials as filler for improving performance of concrete - a review. Australian Journal of Civil Engineering, 17(2), 85–95. https://doi.org/10.1080/14488353.2019.1626692

[3] Grillo, R. (2018). Study of the Influence of Curing Processes on Mechanical Resistance Properties of Concretes. Trends in Civil Engineering and Its Architecture, 2(1). https://doi.org/10.32474/tceia.2018.02.000128

[4] Nagrockiene, D., Pundienė, I., & Kicaite, A. (2013). The effect of cement type and plasticizer addition on concrete properties. Construction and Building Materials, 45, 324–331. https://doi.org/10.1016/j.conbuildmat.2013.03.076

[5] Mohammad Abdul Kreem, O. (2012). Influence of Concrete Mix Proportions and Curing Regimes on Density, Absorption, and Voids in Hardened Concrete. AL-Rafdain Engineering Journal (AREJ), 20(4), 103–117. https://doi.org/10.33899/rengj.2012.54159

[6] Falliano, D., De Domenico, D., Ricciardi, G., & Gugliandolo, E. (2018). Key factors affecting the compressive strength of foamed concrete. IOP Conference Series: Materials Science and Engineering, 431, 062009. https://doi.org/10.1088/1757-899x/431/6/062009

[7] Oto, B., Gür, A., Kavaz, E., Çakır, T., & Yaltay, N. (2016). Determination of gamma and fast neutron shielding parameters of magnetite concretes. *Progress in Nuclear Energy*, *92*, 71–80. https://doi.org/https://doi.org/10.1016/j.pnucene.2016.06.011

[8] Khan, M., & Ali, M. (2018). Effect of super plasticizer on the properties of medium strength concrete prepared with coconut fiber. Construction and Building Materials, 182, 703–715. https://doi.org/10.1016/j.conbuildmat.2018.06.150

[9] Ndagi, A., Umar, A. A., Hejazi, F., & Jaafar, M. S. (2019). Non-destructive assessment of concrete deterioration by ultrasonic pulse velocity: A review. IOP Conference Series: Earth and Environmental Science, 357, 012015. https://doi.org/10.1088/1755-1315/357/1/012015

[10] Biswas, R., Rai, B., & Samui, P. (2021). Compressive strength prediction model of high-strength concrete with silica fume by destructive and non-destructive technique. Innovative Infrastructure Solutions, 6(2). https://doi.org/10.1007/s41062-020-00447-z

[11] Savadkoohi, M. S., & Reisi, M. (2020). Environmental protection based sustainable development by utilization of granite waste in Reactive Powder Concrete. Journal of Cleaner Production, 266, 121973. https://doi.org/10.1016/j.jclepro.2020.121973

[12] Erdem, M., Baykara, O., Doğru, M., & Kuluöztürk, F. (2010). A novel shielding material

[13] Roslan, M. K. A., Ismail, M., Kueh, A. B. H., & Zin, M. R. M. (2019). High-density concrete: Exploring Ferro boron effects in neutron and gamma radiation shielding. Construction and Building Materials, 215, 718–725. https://doi.org/10.1016/j.conbuildmat.2019.04.105

[14] Khatib, J., & Mangat, P. (1995). Absorption characteristics of concrete as a function of location relative to casting position. Cement and Concrete Research, 25(5), 999–1010. https://doi.org/10.1016/0008-8846(95)00095-t

[15] Mesbahi, A., Alizadeh, G., Seyed-Oskoee, G., & Azarpeyvand, A.-A. (2013). A new barite–colemanite concrete with lower neutron production in radiation therapy bunkers. *Annals of Nuclear Energy*, *51*, 107–111. https://doi.org/https://doi.org/10.1016/j.anucene.2012.07.039