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A Comprehensive Review of Plastic Concrete in Relation to Cut-Off Walls

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Abstract: ***The remediation of earthen dams is becoming a topic of significant interest on a global scale. Plastic Concrete cut-off walls provide an efficient means of controlling seepage in dams. However, the behaviour of Plastic Concrete as a material is not yet fully comprehended. The review presented here indicates that Plastic Concrete can be classified as a low-strength, low-stiffness impervious concrete that exhibits a high capacity for deformation under load, while also highlighting the need for further exploration of its mechanical and hydraulic properties. This review presents a valuable opportunity to deepen the understanding of the material behaviour of Plastic Concrete and contribute to a more accurate design of Plastic Concrete cut-off walls.***

Keywords: Plastic concrete, Cut-off wall, Permeability, Ductility, Elasticity modulus.

I. INTRODUCTION

Dams are designed to retain or store water. To effectively reduce the flow of water through the dam and foundation system, it is crucial to create and construct specific impervious zones or elements. Concrete dams are generally considered to be almost impervious, except for potential leakage through construction joints or cracks. For embankment or fill dams, a zone of low permeability soil, asphalt, or concrete is required, which can be positioned either within the dam or in the case of asphalt and concrete facings, along the upstream face. The flow of water through the foundation beneath the dam is influenced by the underlying geological and hydrogeological conditions. Seepage through permeable strata (including alluvial deposits and residual soils) can be controlled by a barrier or cut-off wall composed of a series of impervious elements (such as piles or panels) that extend down to a layer of much lower permeability, usually rock [1] (see Fig. 1). Cut-off walls are a technique employed as an impermeable component in various contexts, such as the foundation of impoundment earth dams, to regulate leakage from the foundation, and in excavation areas situated below the underground water level in major projects like earth dams, concrete dams, and the construction of underground multi-storey parking facilities. They are also used to limit the burying of waste, in the construction of installations and coastal structure foundations, supporting walls, and stabilizing gradients through the use of bar anchors. Additionally, cut-off walls are implemented in underground dams to sustain a high underground water level in alluvial and permeable areas while preventing the mixing of saltwater with freshwater. The most efficient cut-off walls for controlling seepage can be built using excavated slurry-trench walls, particularly for deeper applications.

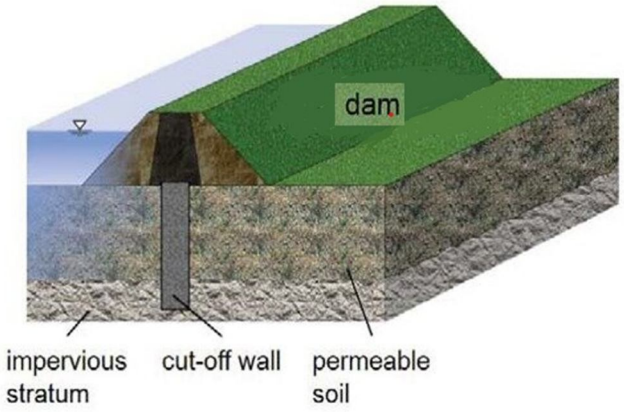


Fig. 1 Schematic representation of a cut-off wall situated beneath an earthen dam

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The initial phase of constructing slurry walls involves excavating a trench to the specified depth, which may vary from few meters to more than 100 meters based on the project's requirements. Excavation is generally carried out using mechanical clamshells, hydraulic grabs, or trench cutters, with the trench being excavated in segments. During excavation, a stabilizing fluid—commonly a bentonite–water or polymer-based slurry—is continuously circulated within the trench to ensure sidewall stability. The thixotropic characteristics of the slurry enable it to create an impermeable filter cake on the trench walls, which prevents collapse and the ingress of ground water. Prior to placing the backfill material, the support fluid utilized during excavation must be substituted with a clean support fluid that possesses defined material properties [2] (refer to Fig. 2). Subsequently, the backfill material is introduced using the tremie method. The backfill material is introduced through the so-called tremie pipe, ensuring that the lower end of the tremie pipe remains submerged below the concrete surface (refer to Fig. 2). Commonly used backfill materials for slurry trench cut-off walls include soil–bentonite (SB), cement–bentonite (CB), soil–cement–bentonite (SCB), and plastic concrete (PC), all of which are typically placed using the tremie technique to achieve a continuous and homogeneous barrier.

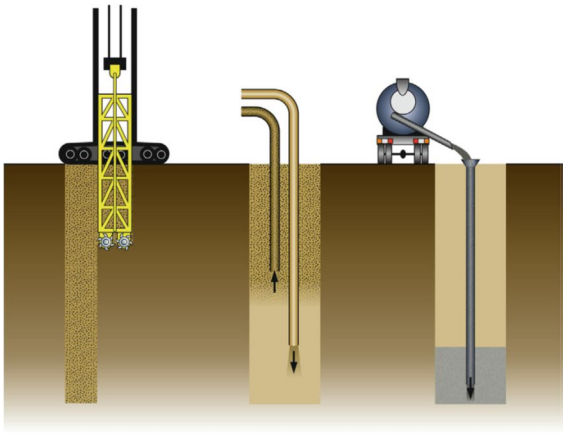


Fig. 2 An overview of the construction process for a slurry trench wall utilizing a hydromill trench cutter (left), the replacement of support fluid (center), and the placement of plastic concrete through the tremie method (right)

Plastic concrete is a specialized backfill material that integrates aggregates into a cementitious mixture, offering enhanced strength and ductility compared to SB and CB, thus making it appropriate for applications with high deformation requirements. This capacity for high deformation is a significant benefit of plastic concrete, particularly in situations involving considerable bending strains due to seismic activities or fluctuations in reservoirs. Additionally, this characteristic reduces both the likelihood of rupture and the width of crack openings, thereby minimizing the chances of increased permeability in the cut-off wall [3,4,5,6]. Like ordinary concrete, Plastic Concrete consists of cement, water, aggregate, additives, and admixtures, albeit in different proportions [5]. Most importantly, Plastic Concrete is manufactured with a very high water-to-cement ratio and water-binding additives (such as bentonite) to ensure the stability of fresh concrete, resulting in a highly ductile and impermeable material [5].

Notwithstanding its undeniably advantageous material characteristics, the mechanical behaviour of Plastic Concrete remains an area that requires extensive investigation [5]. At present, the design of cut-off walls treats Plastic Concrete as a linear-elastic material, characterized by a specified compressive strength at 28 days [7], due to the absence of a specific constitutive law for Plastic Concrete that could reflect the temporal evolution of its mechanical properties [5]. This situation is largely attributed to the limited systematic data available in the literature, which prevents the correlation of compressive strength, tensile strength, and elastic modulus from a single mix design. The absence of a dedicated constitutive law typically results in higher cement contents than are technically required, ensuring that the strength criteria are consistently satisfied in the linear-elastic design [7]. Consequently, the material's full potential is only partially realized, and the inherent sustainability benefits are not fully realized [7]. The resultant increase in costs may also pose significant challenges to the adoption of Plastic Concrete in developing nations [8,9]. Therefore, the following subsections will summarize the current understanding of the mix design, including the materials utilized as well as the variations in mixture composition and their impact on the fresh properties and mechanical and hydraulic behaviour of Plastic Concrete.

This paper aims to provide a critical review of the current literature surrounding Plastic Concrete and suggests general statements and reference values that can enhance the design of Plastic Concrete to more accurately represent the behaviour of the material.

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II. MIX DESIGN

A. Materials

Present-day standard concrete is regarded as a five-phase construction material consisting of cement, water, aggregate, additions (like supplementary cementitious materials), and admixtures. Plastic Concrete can also be identified as a five-phase construction material, but with different ratios than those typically combined with standard concretes, and it contains bentonite as an additional ingredient to create a highly ductile and impermeable material. Nevertheless, the formulation of Plastic Concrete is not restricted to the components mentioned above and may be created using alternative supplementary cementitious materials or other physically water-binding additives.

1) Cement

For Plastic Concrete, there are two main alternatives. The International Commission on Large Dams (ICOLD) advises in its Bulletin 51 [14] the utilization of blast-furnace or pozzolan cement, as these cement types exhibit enhanced resistance to chemically aggressive water, a fact well recognized in concrete technology [10,11,12]. It is also acknowledged in concrete construction that the use of blast-furnace cement results in a significantly slower development of concrete strength at an early age compared to ordinary Portland cement [3,10,12,13]. Consequently, when the secondary panel is cut between two primary panels that were previously placed using the tremie method, it is generally accepted that the primary panels have reached a certain minimum concrete strength. Furthermore, the local availability of blast-furnace or pozzolan cements may also pose a constraint in the selection of cement types.

2) Bentonite

Bentonite is a type of hydrated clay mineral that is primarily made up of montmorillonite. Its chemical makeup predominantly consists of silica, alumina, and water [15,16]. Depending on the type and ratio of interlayer ions in montmorillonite, bentonites can be classified into calcium bentonite (Ca-bent), sodium bentonite (Na-bent), and magnesium bentonite (Mg-bent) [17–22]. The water adsorption capabilities of sodium and calcium bentonite, however, differ significantly, with Ca-bentonite capable of adsorbing 200–300% of water, while Na-bentonite can absorb as much as 600–700% of water [40,41]. This phenomenon of water adsorption results in a significant increase in the volume of clay minerals, especially montmorillonite, which can multiply its initial volume manifold. Because bentonite exhibits excellent water swelling properties and is considered non-toxic and safe, it can be added to mortar to fill tiny pores, thereby reducing water migration in the pore structure and providing exceptional waterproofing and impermeability characteristics [23–26]. Some researchers have developed a humidity-adjustable mortar for the automatic regulation of indoor humidity [27]. Moreover, researchers have incorporated bentonite into mortar and concrete by substituting part of the cement. The compressive strength of the modified sample was comparable to that of the original sample, and its resistance to sulfate attack was consistently enhanced, indicating that bentonite can be employed as a low-cost auxiliary material [28–32]. Bentonite can also be applied as an impervious waterproofing material. Bentonite absorbs free water and swells in the mortar, which densifies the paste, thus reducing the porosity of the mortar; the formation of more calcium-silicate-hydrate (C-S-H) through the pozzolanic reaction between bentonite and calcium hydroxide is also beneficial for improving the impermeability of the mortar [33,34]. For example, in reservoir dams, concrete with high plasticity and low permeability can be obtained after incorporating bentonite [35,36]. Studies have shown that the addition of bentonite to the cement matrix used to cure radioactive waste and heavy metals can effectively reduce the leaching rate of the radionuclides and heavy metals [37–39]. While most of the above studies used bentonite, the chemical composition of bentonite in different regions varies, making it difficult to compare their results. More recent research has also found that other physically water-binding additions (e.g. sepiolite, silty clay, etc.) can be used to effectively produce Plastic Concrete, although with some limitations [42,43]. Bentonite has however remained of utmost importance in recent years, since bentonite's heavy metal absorption capacity has led to growing interest in the application of bentonite for containment barriers for waste water or radioactive waste [36,42,44].

3) Aggregate

The primary factor in selecting aggregates for Plastic Concrete is the maximum grain size, owing to the significant risk of segregation in fresh Plastic Concrete. This issue arises from the relatively high water-to-cement ratio and the necessity of incorporating bentonite as a stabilizing agent. Consequently, aggregates are typically restricted to sands and fine to medium gravels. Most specifications stipulate a maximum grain size of $d_{max} \leq 22$mm [4,45], while practical applications usually limit the maximum grain size to $d_{max} \leq 12.5$ mm. Additionally, the content of fine particles is also somewhat regulated to ensure the required flowability [45].

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Rounded aggregates are generally favored, as this type of aggregate further improves the flowability of tremie concrete [46]. Furthermore, the type of aggregate utilized is governed by the exposure to any aggressive contaminants, with quartz-based aggregates being the preferred choice [46].

4) Admixture

Different kinds of admixtures are utilized in the design of Plastic Concrete mixes. Typically, retarding admixtures are employed to delay the setting of concrete and to avert premature stiffening during tremie placement [4]. This approach allows for an extended workability period, enabling the safe completion of concrete placement for longer slurry trench elements using the tremie method. The quantity of retarding admixtures added can vary based on the composition of the Plastic Concrete mixture, generally falling between 1 wt.% and 2.5 wt.% of the cement content, with particular caution required when constructing long slurry trench elements [47].

In specific instances, superplasticizing admixtures are employed to provide enhanced and more controlled workability of the Plastic Concrete mixture. It should be emphasized that the performance of modern polycarboxylate ether-based superplasticizers (PCEs) is detrimentally affected by the presence of clay minerals, especially montmorillonite [47]. Typically, tap water is suitable for the production of Plastic Concrete. However, untreated water or water with high ion concentrations may influence the dispersion of bentonite or the hydration process, and should therefore be tested in trial mixtures if needed [48].

B. Composition of Mix

The historical approach to designing plastic concrete mixes has largely been based on trial and error. A functional design procedure was formulated by the US Army Corps of Engineers (USACE) in the early 1990s (14,49). The fundamental approach was to link the outcomes of straightforward tests with clearly defined material and testing parameters. An extensive testing program was implemented, which encompassed unconfined compression tests, isotropically consolidated undrained (CIU) triaxial tests and permeability tests. The triaxial tests were mainly conducted to explore the impact of consolidation and horizontal confinement on the stress-strain-strength behavior and the permeability characteristics of the plastic concrete.

The fundamental components of plastic concrete include cement, bentonite, aggregate, and water. To measure these material parameters and create design data from tests conducted on different mixtures, Kahl et al. (49) outlined the following batch parameters:

- Cement factor (CF): This refers to the total weight (in pounds or kg) of cement and bentonite present in a unit volume (cu yard or m^3) of plastic concrete, i.e.

$$CF = (W_{cement} + W_{bentonite})\ (kg/m^3)$$

- Bentonite content (BC): This indicates the proportion of the cement factor that consists of bentonite, calculated as, i.e.:

$$BC = [W_{bentonite}\ (kg/m^3)/CF\ (kg/m^3)]\ x100\ (\%)$$

- Water-cement ratio (w/c): This represents the ratio of the weight of water to the combined weight of cement and bentonite, defined as, i.e.

$$w/c = W_{water}/(W_{cement} + W_{bentonite})$$

- Coarse to fine ratio: This is the ratio of coarse aggregate to fine aggregate based on weight.

Using the aforementioned parameters, the process for designing a plastic concrete mix for laboratory testing is as follows:

1) For a specified cement factor and bentonite content, estimate the water-cement ratio that would yield a slump of 20 cm.
2) Determine the actual weights and volumes of cement, bentonite, and water (in kg and m^3) necessary to create 1 m^3 of plastic concrete.
3) Compute the required volume of fine and coarse aggregate by subtracting the total volumes of cement, bentonite, and water from one cubic meter.
4) Derive the weights of fine and coarse aggregate based on their respective volumes.
5) Adjust the weights of all components for hygroscopic moisture content and scale the quantities to achieve the desired batch volume.
6) Upon completion of batching, adjust the cement factor and the water-cement ratio for any extra water added during the mixing process.

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The aggregate ratio (fine aggregate to coarse aggregate) is typically considered to be 1.0 for tremie concrete.

In comparison to conventional concrete, the water-to-cement ratio of Plastic Concrete is significantly higher, with values between 3.3 and 10 [14]. The cement content is also markedly lower than that of standard concrete, seldom exceeding 200 kg/m3 and occasionally dropping to as low as 80 kg/m^3. Additionally, Plastic Concrete incorporates bentonite, with its content varying from 0.5% to 12% by weight of the dry mass of constituents, depending on the mixture's composition and the type of bentonite used. Generally, lower bentonite contents are associated with Na-bentonite, while higher contents are linked to Ca-bentonite, attributed to their differing swelling behaviors. Some researchers propose a Na-bentonite to Ca-bentonite ratio of 1:5, indicating a more cost-effective method through the utilization of Na-bentonite [53]. Moreover, Plastic Concrete contains slightly smaller amounts of aggregate compared to standard concrete, with quantities ranging from 1100 kg/m^3 to 1500 kg/m^3.

C. Blending Sequence

The mixing procedure for Plastic Concrete is inconsistent throughout the literature. A variety of options are presented, which are schematically represented in figure 3.

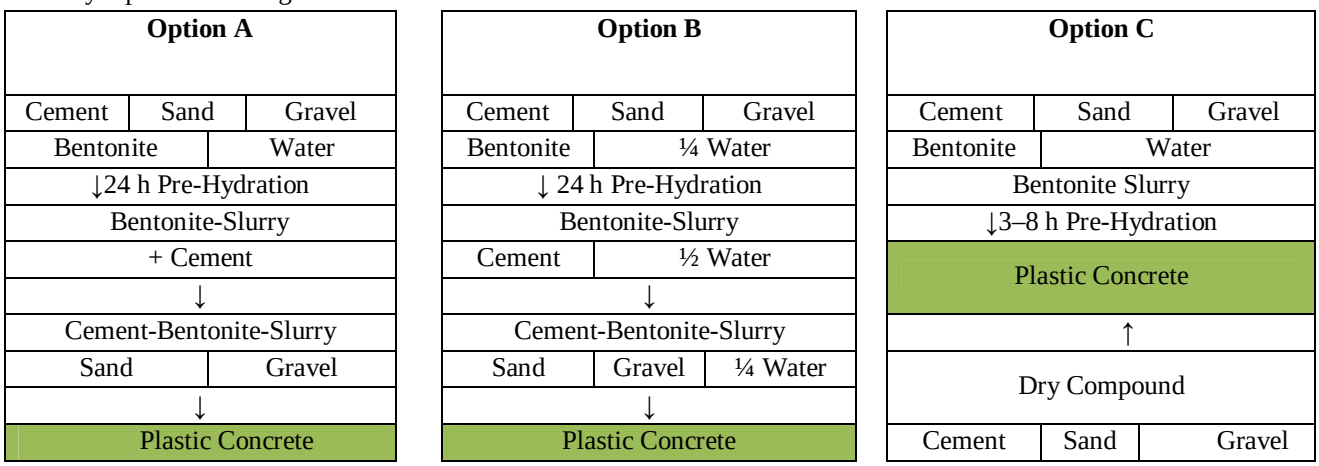


Fig. 3 Illustrative instances of Plastic Concrete mixing sequences

Option A is the variant most frequently referenced in literature [54-61]. In this method, bentonite and water are gradually combined and allowed to hydrate for a duration of up to 24 hours. Following this, cement is incorporated into the bentonite suspension, and subsequently, the aggregates are introduced. Option B [42] follows a similar mixing procedure to Option A; however, the water addition is divided into three distinct stages. The bentonite slurry is also hydrated for a maximum of 24 hours before the addition of cement, sand, gravel, and the remaining water occurs in two separate phases. Lastly, Option C represents a commonly utilized mixing sequence in practical applications, where cement and aggregate are blended into a dry mixture, while bentonite and water are combined into a slurry [62]. This bentonite slurry is then integrated with the dry mixture to create the Plastic Concrete mixture, with the bentonite slurry being hydrated from 0 to 8 hours prior to use. It is important to note that due to the variations in mixing sequences and hydration durations, different outcomes can be anticipated regarding mechanical properties and permeability values. This is likely due to the differing hydration phases of bentonite for the three previously mentioned options, which subsequently influences the void filling in the hardened cement paste. Furthermore, the hydration of bentonite is not solely dependent on the aforementioned differences among bentonite types (refer to Section 2.1.2) but also on the type of mixer used and the resulting shear rate $\dot{\gamma}$. For any specific mixer, it can be observed that a higher maximum achievable shear rate $\dot{\gamma}$ correlates with a reduced hydration time required for bentonite samples [53].

To this point, only Fadaie et al. have examined how dry and saturated bentonite affects the mechanical properties of Plastic Concrete [35]. Their research revealed that the mechanical properties are almost the same for samples with dry bentonite and those with bentonite that had been hydrated for 24 hours. Additionally, the disparity in mechanical properties diminishes as the age of the samples increases [35]. Due to the lack of substantial scientific literature on the impact of the mixing sequence on Plastic Concrete properties, this area should be thoroughly investigated in future research.

D. *Fresh properties*

To facilitate the correct placement of concrete, which in turn improves the quality of hardened concrete, it is vital to control the fresh properties of Plastic Concrete mixtures, particularly the flowability of the concrete throughout the entire casting process. Consequently, the fresh properties must be assessed not only during the initial placement but also to evaluate the thixotropic and flow retention characteristics of the concrete [63].

The flow properties are primarily influenced by the rheology of the concrete, which is a result of the concrete mix design [63]. Despite the intricate nature and significance of concrete rheology, it is still relatively common to employ basic concrete testing methods to ascertain the fresh properties of concrete [63].

It is important to recognize that numerous issues in diaphragm walls can be linked to the use of inadequate concrete mixes stemming from poor concrete specifications due to insufficient or overly simplistic testing methods [63, 64]. Typically, the so-called slump test and flow table test are utilized, although alternative tests are available.

For Plastic Concrete that is placed using the tremie method, there are various guidelines and standards that stipulate specific values for the fresh properties of the concrete. As per Appendix D of DIN EN 206 [65], the flow table test values for concrete placed via the tremie method should reach 600 mm. Alternatively, a slump test may be conducted with a target value of 200 mm. In a similar vein, the Austrian standard ÖNORM B4452 [45] mandates that the concrete achieve flow table test values between 550 mm and 650 mm.

This standard also imposes a limit on the free-fluid test value, as outlined in DIN EN ISO 10426-2 [66], which is typically employed to assess sedimentation stability, capping it at 2% after 2 hours [45]. The DWA guideline M512-1 [67] advises that the flow table test value for Plastic Concrete should exceed 530 mm. Likewise; the USBR Design Standard 13(16) specifies a desired slump of 150 mm to 230 mm to ensure optimal fluidity and workability [4]. Additionally, the density must be measured in accordance with EN 12350-6 [68] when the dosing of Plastic Concrete is volumetric.

Other evaluations, such as the L-Box test according to DIN EN 12350-10 [69], although created for super-workable concrete, are not entirely appropriate for Plastic Concrete. The high flowability and low maximum aggregate size make it challenging to contain the concrete within the L-Box.

This limitation prevents the calculation of the passing ability ratio (PL). Furthermore, some guidelines also reference the Marsh funnel viscosity in accordance with DIN 4127 [70] or ASTM D6910 [71] when assessing the flowability of fresh concrete. It is noteworthy that the Marsh funnel has a maximum opening of 4.75 mm at the bottom and an entry screen of 3.2 mm, which primarily permits the measurement of bentonite slurries without aggregate. Nonetheless, ICOLD Bulletin 51 mandates a Marsh funnel viscosity of 50 seconds for the bentonite slurry [14].

The flowability of concrete is generally managed through the control of water and superplasticizing agent levels; however, it is crucial to monitor the stability of Plastic Concrete closely. Evans et al. [57] also propose that the workability of Plastic Concrete is improved by adding fly ash, which acts similarly to ball bearings. For more in-depth information on the various testing methods for fresh concrete relevant to the tremie method, please refer to the EFFC/DFI Guide to Tremie Concrete for Deep Foundations [64].

III. HARDENED CONCRETE PROPERTIES

The properties of hardened concrete in concrete samples are most commonly associated with the compressive strength of the samples. However, for the design of cut-off walls, understanding the tensile strength of plastic concrete, along with its multi-axial strength, is equally crucial.

A. *Unconfined Compressive Strength*

The characteristics of Plastic Concrete's strength can be defined by several parameters; however, the unconfined compressive strength (UCS) is most frequently utilized. In the field of concrete technology, the water-cement (w/c) ratio is the primary parameter influencing concrete strength, with a lower w/c ratio resulting in increased concrete strength [10,12]. The investigation performed by Kahl et al. (1991) [1] established a correlation between the unconfined compressive strength values (obtained from specimens with a diameter of 150 mm and a height of 300 mm) and the water-cement ratio across all bentonite contents. These relationships are represented in figure 4.

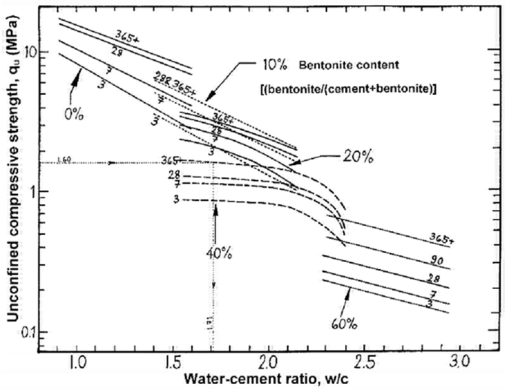


Fig. 4 Unconfined compressive strength versus water-cement ratio for all bentonite contents with lines being isochrones of curing age (Kahl et al., 1991)

The graph indicates that, as expected, there is a steady decline in the strength of Plastic Concrete with a rising w/c-ratio. Furthermore, it is noted that an increase in bentonite content necessitates more water for hydration, which raises the w/c-ratio and subsequently reduces strength.

In concrete technology and design, standard concrete normally achieves a fracture strain of approximately 0.2%–0.3% when tested under standardised unconfined compression conditions [10]. It is furthermore of common knowledge that the fracture strain increases with increasing concrete strength, however the post cracking behaviour is far more brittle the higher the concrete strength is [10]. Plastic Concrete is therefore expected to have a higher fracture strain than ordinary concrete and a far more ductile post-peak behaviour. This behaviour has been corroborated by various studies, which identify an achievable strain at failure for Plastic Concrete between 0.5% and 1.0% in unconfined compression tests [56,73,74]. However, the aforementioned guide values are also dependant on loading speed, since concrete is a crack sensitive material [13]. Consequently as the loading speed increases, the observed strength of the concrete also rises, as the likelihood of crack propagation around aggregate particles diminishes, thereby promoting particle rupture [13,75]. At extremely high loading rates, further inertial effects may manifest [13]. Conversely, at very low loading speeds, creep deformation may occur alongside elastic deformation, leading to concrete testing that reveals a lower compressive strength [10,13,75].

Consequently, the standards pertaining to the testing of compressive strength in concrete specify a particular loading speed. In IS 516 (Part 1/Sec 1): 2021 [76], the loading speed for concrete specimens is established at 14 N/mm2/min (0.23 MPa/s), whereas EN 12390-3 [77] stipulates a loading speed of 0.6 ± 0.2 MPa/s, ensuring that specimen failure occurs within 60 to 90 seconds. The German National Annex indicates that the loading speed may also be modified for specimens with compressive strengths exceeding 80 MPa or falling below 20 MPa. ASTMC39/C39M [78] specifies that a movement rate corresponding to a specimen stress rate of 0.25 ± 0.05 MPa/s should be utilized. Conversely, geotechnical testing standards for soil, such as IS 2720 (part 10) [79], DIN 18136 [80], and ASTM D 2166/D 2166M [81], define the loading speed based on strain rate, which should be maintained at 0.5% - 2% of the sample height per minute.

Kazemian et al. [82] discovered that the stress-strain characteristics of Plastic Concrete are distinct from those of conventional concrete (not linear between 0% and 40%). Furthermore, it is anticipated that the standard loading speed is typically too elevated to accurately measure stress-strain. The research conducted by Hinchberger et al. [83], which involved strain-controlled experiments, also indicated that Plastic Concrete exhibits sensitivity to different compression rates. Specifically, increased compression rates (0.01 mm/min > 0.001 mm/min) lead to elevated compressive stress values [83]. Consequently, it is advisable to modify the standard loading speed in concrete testing protocols for Plastic Concrete specimens to obtain measurable and accurate data. Given that the compressive strength of Plastic Concrete at 28 days ranges from 1 to 3 MPa, it is recommended that samples be tested at a reduced loading speed of between 0.02 MPa/s and 0.03 MPa/s. For instance, in DIN 4093 [54], which governs the design of reinforced soil through jet grouting, deep mixing, or grouting methods, the loading speed is lowered to 0.05 MPa/s for samples anticipated to have a compressive strength of less than 4 MPa. This adjusted loading speed would also align with the requirements for Plastic Concrete and would result in failure after approximately 20 seconds.

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The comprehension of the long-term strength development of Plastic Concrete holds great significance, given that cut-off walls are built for longer design durations. Therefore, it is not imperative to assess the characteristic compressive strengths of Plastic Concrete samples at 28 days; testing can be performed at an older age. Nevertheless, caution is recommended, as inadequate strength development could hinder the efficiency of construction operations due to the alternating sequence of primary and secondary panel construction, necessitating consideration during the design phase.

B. Tensile strength

Executing the direct tensile test is quite challenging; hence, indirect tensile strength tests, specifically split and flexural strength tests, are conducted [85]. Split tensile strength is a vital property of concrete, utilized in the design of structural elements that experience transverse shear, torsion, shrinkage, and other stresses [76]. Typically, square root functions are employed to derive tensile strength from compressive strength (fck) [86]. The IS Code 456-2000 [87] does not provide a direct equation for split tensile strength; instead, it offers a formula for flexural strength (fcr) based on cube compressive strength: $fcr = 0.7\sqrt{fck}$. The American Concrete Institute (ACI) model advocates for a square root relationship between splitting tensile strength and cylinder compressive strength. Furthermore, the fib Model Code 2010 indicates that the mean tensile strength fctm can be approximated from the characteristic compressive strength fck using the equation $fctm = 0.3 \times fck^{2/3}$.

It should be acknowledged that the mean tensile strength (fctm) relates to uniaxial conditions, while the tensile strength testing of concrete specimens is predominantly performed using the splitting tensile strength (fct). The literature has not yet provided a definitive conversion between these two values. For Plastic Concrete, the USACE REMR-GT-15 report is the sole document that also examines the splitting tensile strength of concrete, with the splitting tensile strength averaging 13% of the ultimate compressive strength fu of the tested samples [49]. The specific relationship between tensile strength and compressive strength or Plastic Concrete remains uncertain and should thus be a vital aspect of future studies. It may seem practical, in the context of concrete technology, to estimate the tensile strength of Plastic Concrete to be within the range of 10% to 20% of its compressive strength.

C. Multi-Axial Load-Bearing Capability

Structural concrete is frequently subjected to multi-axial loading conditions within a structure, which makes the multi-axial load-bearing capability of concrete critically important. It is essential to first acknowledge that concrete failure under a uni-axial compressive force arises from the inherent development of a transversal tensile stress, leading to the exceedance of the concrete's tensile strength [13]. In this context, the concrete specimen fails due to the formation of cracks that run parallel to the direction of the primary loading, demonstrating a brittle behavior [12]. However, this lateral strain can be impeded by applying a compressive force perpendicular to the primary loading direction, which subsequently enhances the overall compressive load-bearing capacity of the concrete specimen [13]. Conversely, if a perpendicular tensile strength is applied, the overall compressive load-bearing capacity diminishes. Likewise, when tri-axial compression is applied with significant lateral stresses, the concrete's load-bearing capacity increases substantially [12]. This increase is known to be more pronounced when the UCS is lower and the moisture content of the concrete is reduced [10]. However, failure no longer occurs due to the exceedance of tensile strength but rather through crushing, resulting in a shift towards ductile behavior [12]. Depending on the stress relationship among the three present stresses, concrete failure manifests through the formation of shear bands and shear failure [10,13].

In cut-off walls, Plastic Concrete is inherently subjected to a multi-axial stress state. Nevertheless, the stress relationship may fluctuate based on dam settling and the upstream water level [88]. Thus, it is crucial to comprehend the multi-axial behavior of Plastic Concrete. One can anticipate a behavior in Plastic Concrete that is akin to that of standard concrete. Given the low uniaxial compressive strength, the increase in multi-axial load-bearing capacity is expected to be more significant. However, this enhancement is likely constrained due to the elevated water and moisture content present in Plastic Concrete samples. Numerous studies have corroborated the alteration in failure mode with rising confining pressure for Plastic Concrete samples [56,58,59,61]. At low confining pressures, cracking occurs parallel to the specimen load axis [58], which some researchers attribute to the gradual degradation of cohesive bonds [59]. In contrast, at higher confining pressures, specimen failure manifests through the presence of a failure plane or a mixed failure mode [58], indicating the prevailing frictional characteristics in specimen failure [59,60,67]. Specimens subjected to higher confining pressures not only demonstrate an increased compressive load-bearing capacity and elastic modulus [61], but also exhibit a more ductile, and potentially strain-hardening behavior, along with an overall higher strain at failure [59,60,61,67]. Numerous studies have demonstrated that under confining pressures ranging from 200 kPa to 800 kPa, a failure strain of between 2% and 10% can be attained, highlighting the significantly ductile nature of Plastic Concrete [59,60,61,67].

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D. Modulus of Elasticity (Elastic Modulus)

The elastic modulus (E) of concrete is mainly influenced by the elastic moduli of its constituent components, namely cement paste and aggregate, along with the volumetric proportions of these materials in the mix. This can be estimated using composite theory [13]. The elastic modulus of cement paste is primarily affected by capillary porosity, which is in turn influenced by the water-cement (w/c) ratio and the degree of hydration. Aggregates typically possess a higher elastic modulus, which is largely determined by the mineralogical characteristics of the rock. Consequently, it can be stated that an increase in water content or a reduction in cement content leads to a decrease in the elastic modulus of the resulting concrete [13]. Additionally, it is widely recognized that as the degree of hydration increases, the elastic modulus also rises, with this increase in elastic modulus occurring prior to any increase in compressive strength [10].

Plastic Concrete exhibits characteristics akin to those of conventional concrete. The elastic modulus of Plastic Concrete rises with age while diminishing as the bentonite content increases [59,60]. Moreover, the elastic modulus declines with a higher water-cement ratio, consistent with the behavior of standard concrete [55,58,59,89]. Several studies have indicated that the bentonite content also influences the development of the elastic modulus over time, paralleling the progression of strength [59,60]. Additionally, the elastic modulus further escalates with increased confining pressure during tests conducted in the triaxial testing apparatus [58,59,60]. The elastic modulus of concrete is influenced by the testing procedure employed. The "elastic modulus" established through concrete testing standards (Zhang et al. [89]) is greater than that derived from geotechnical testing standards (e.g. Mahboubi et al. [59]). This discrepancy is likely attributable to the deformation measurement methods utilized, as concrete standards assess specimen deformation in-situ (e.g. using strain gauges), whereas geotechnical standards typically rely on machine displacement to determine specimen deformation. Comparable findings have been reported in research concerning cement treated soils [90]. This further reinforces the notion that the testing conditions should be clearly defined during the planning and tendering phases of projects.

The study conducted by Kahl et al. (1991) [1], illustrated in figure 5, established a relationship between unconfined compressive strength and elastic (or Young's) modulus across all curing ages and bentonite contents. The graph features two regression lines due to the elastic moduli being derived from two distinct methods of strain measurement; specifically gross deflection and compressometer (refer to ASTM C465). Although the second measurement method appears to be more precise, the data exhibits greater variability than the differences observed in the strain values. The graph distinctly indicates that the elastic modulus rises in conjunction with the unconfined compressive strength.

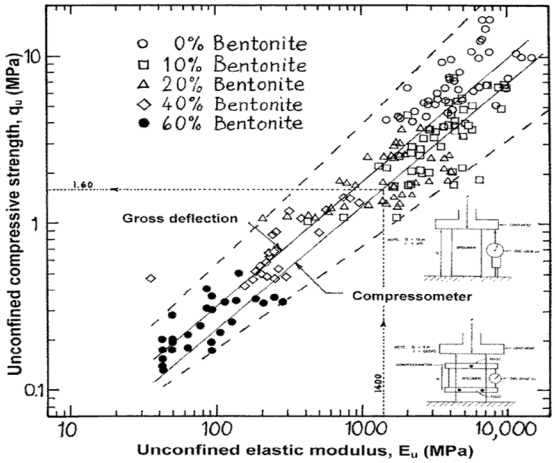


Fig. 5 Relationship between unconfined compressive strength and elastic (Young's) modulus for all curing ages and bentonite contents (Kahl et al., 1991)

Several studies also explore how modifications in the composition of Plastic Concrete can affect its compressive strength [54,91]. For instance, Bagheri et al. examine the impact of replacing cement with silica fume [54]. Notably, a 15% cement substitution results in a 180% increase in the Elastic Modulus for Plastic Concrete (w/c=1.8), whereas normal concrete (w/c=0.4) experiences only a 30% increase with the same substitution. Given that silica fume is recognized for its ability to enhance the quality of the transition zone [12], this 180% increase may indicate that the transition zone is particularly weak in Plastic Concrete mixtures. The authors further note that, for Plastic Concrete, the incorporation of silica fume does not significantly change the correlation between elastic modulus and compressive strength.

Furthermore, the desired elastic modulus of Plastic Concrete should align closely with that of the surrounding soil and must not exceed five times that of the latter [14,92]. This has been corroborated by various numerical studies examining the deformation of cut-off walls under high overburden or seismic loads, which demonstrate that a higher elastic modulus of the backfill material leads to increased strain and stress within the cut-off wall, potentially resulting in seepage or even failure of the cut-off wall [6,93].

E. Creep and Relaxation

When concrete is placed under a load, it initially responds elastically. However, beyond the elastic strain components, concrete exhibits a non-linear stress-strain behavior. Under prolonged loading, strain progressively increases over time due to concrete creep. The creep coefficient (φ) is recognized as the predominant engineering method for estimating concrete creep. It is defined in accordance with the fib Model Code 2010 as the ratio of the concrete creep strain ε_{cc} to the concrete elastic strain ε_{ci}, as expressed below [13,94].

$$\varphi(t,t_0) = \frac{\varepsilon_{cc}(t,t_0)}{\varepsilon_{ci}(t_0)}$$

Various factors influence the creep behavior of concrete specimens. As the cement content and water content increase, the creep of concrete also rises, as it is the cement paste phase that experiences creep [12]. Normal weight aggregates typically do not exhibit sensitivity to creep; rather, they serve to restrain concrete creep. This restraint is more significant when the elastic modulus of the aggregate is higher [13]. Additionally, some researchers propose that the grading, maximum size, and shape of aggregates also play a role in concrete creep [12]. Moreover, creep is affected by the ambient relative humidity, with creep being more pronounced at lower surrounding relative humidity levels [12,13]. Furthermore, concrete creep increases in proportion to stress within the service stress range [12,13]. Lastly, it is important to note that concrete creep is also dependent on the age at which loading occurs, with creep increasing disproportionately the younger the concrete is at the time of loading [95]. Consequently, depending on the prevailing conditions, the final creep coefficient φ_∞ can vary significantly, usually falling within the range of $1 < \varphi_\infty < 3$ for standard concrete [13].

In contrast, if a stressed concrete specimen is subjected to a constant strain, the stress within the specimen will gradually decline over time, a process known as relaxation. Both creep and relaxation are governed by the same molecular mechanisms, indicating that all factors influencing concrete creep will similarly affect concrete relaxation [10].

Taking into consideration the aforementioned influencing factors, it is reasonable to expect that Plastic Concrete will exhibit greater creep and relaxation behavior than standard concrete, as various studies have confirmed these expectations [58,74,96]. Firstly, the extremely high water-to-cement ratio likely leads to significant water loss and deformation of the specimen. Additionally, due to the very slow strength development of Plastic Concrete mixtures, the loading of the specimen is likely to occur at a low degree of hydration, which further contributes to concrete creep. Beckhaus et al. suggest a final creep coefficient $\varphi\infty \geq 2$ for Plastic Concrete samples, which was derived from results obtained from soil samples solidified using the jet grouting technique [96]. However, it is expected that Plastic Concrete mixtures may possess even higher creep coefficients (e.g., $\varphi\infty \geq 3$). Hinchberger et al. [58] examined the effect of constant axial strain on the stress behavior of Plastic Concrete and found that it exhibits significant stress relaxation effects, with the measured stress decreasing by approximately 30% after an 8-hour period, and this reduction had not yet stabilized at that point. Overall, Plastic Concrete is expected to demonstrate a stronger relaxation behavior than standard concrete, thus necessitating a time-dependent constitutive model for Plastic Concrete [96].

F. Hydraulic Conductivity (Permeability)

The primary objective of a cut-off wall is to manage seepage in earthen dams. Consequently, the hydraulic conductivity of Plastic Concrete is a critical parameter that requires testing. However, there is currently no established testing standard for assessing the permeability of Plastic Concrete. As a result, standard testing methods from both geotechnical engineering and concrete technology are employed. Hydraulic conductivity testing for concrete specimens is primarily divided into two key groups: those tested under loaded conditions and those tested without any load. In concrete technology, the assessment of material hydraulic permeability is generally performed without simultaneous loading. This can be done on fresh, unloaded samples or on samples that have been loaded previously. The most widely used testing standard for determining the water tightness of structural concrete samples is DIN EN 12390-8 [97], which measures the depth of water penetration under pressure. In this method, a concrete specimen is placed in a pressure apparatus and exposed to a water pressure of 0.5 MPa for 72 hours. After this period, the specimens are split, and the penetration depth is recorded.

While most of the data analyzed relates to testing methods that assess permeability after loading, in various real-world applications (including Plastic Concrete), concrete experiences compressive or flexural forces while being permeated at the same time. There are few testing methods available for this purpose; nevertheless, geotechnical triaxial cells may be employed to ascertain the hydraulic conductivity (k) [98].

Furthermore, owing to its limited strength, water-tightness degree, and composition, Plastic Concrete is typically evaluated according to geotechnical testing standards rather than structural concrete penetration tests. It is evident that, akin to standard concrete, the hydraulic conductivity of Plastic Concrete samples diminishes as compressive strength increases [54, 56,57,91,99]. This phenomenon can be attributed to a decrease in particle cross-linking and an increase in air void content as the w/c-ratio rises, which corresponds to a reduction in compressive strength. Additionally, it should be emphasized that the present design approach for Plastic Concrete does not incorporate the highly ductile behavior of this material, which has been shown to exhibit a significant potential for relaxation and creep. This behavior is advantageous for the hydraulic permeability of Plastic Concrete, as it can help to prevent material stress peaks during loading and avoid the development of cracks, which would result in an increase in permeability. Some preliminary studies have indicated that with a deformation of roughly 70% of strain at failure, there is no considerable increase in hydraulic conductivity [74]. In contrast, crack initiation in concrete generally occurs at approximately 20% of strain [74].

There are only a few studies that also discuss the time-dependent behavior of hydraulic conductivity in Plastic Concrete, reporting a decline in hydraulic conductivity over time [56,100]. This observation aligns with the strength development behavior of Plastic Concrete and is likely caused by the progression of hydration and the consolidation of the concrete microstructure [101]. Additionally, factors such as crack self-healing and the obstruction of cracks by transported particles are also recognized as contributing to the further decrease in concrete permeability over time [102]. Owing to the time-related development of Plastic Concrete permeability, certain specifications permit permeability evaluations at older ages (e.g., 90 days) to achieve the necessary design permeability values [45,48]. However, it may also be contractually prudent to establish 28-day control values, not as the design permeability but as a demonstration of the achievement of design values, in order to shorten the acceptance period for the construction services delivered [48].

IV. CONCLUSION

This paper intends to deliver a detailed comprehension of the behavior of Plastic Concrete materials. With the insights obtained, Plastic Concrete can be reliably employed to ensure seepage control both inside and beneath dams, with a focus on controlled material behavior. Overall, the following factors should be considered in the design of Plastic Concrete cut-off walls.

Plastic Concrete is regarded as a low strength concrete that possesses a low elastic modulus, enabling it to endure greater strains compared to conventional concrete. These characteristics can be achieved through careful selection of raw materials and an optimized mix design. The most distinctive factor that sets Plastic Concrete apart from standard concrete is its significantly higher water-to-cement ratio, which necessitates the management of fresh concrete stability through minimal amounts of physically water-binding additives. Typically, bentonite, a clay-rock made up of montmorillonite minerals, is incorporated, although other additives may also be utilized. Ultimately, Plastic Concrete employs standard aggregate with a maximum grain size of 12.5 mm (to mitigate the risk of segregation) and includes retarding admixtures to postpone the setting of concrete during tremie placement.

Plastic Concrete mix design closely resembles that of standard concrete, featuring aggregate content that spans from 1300 to 1900 kg/m3 and cement content that lies within the range of 80 to 200 kg/m3. The water-to-cement ratio usually varies between 2.0 and 5.0, depending on the target strength and the properties of the constituent materials. Additionally, the sequence in which the components are mixed has been shown influence the fresh and hardened properties of plastic concrete, although no standardized mixing sequence currently exists.

Plastic Concrete exhibits mechanical behavior consistent with what is anticipated from concrete technology. Nevertheless, it is essential to recognize that much of the testing is carried out using geotechnical testing standards instead of concrete testing standards. This is especially relevant when evaluating the deformability of Plastic Concrete, including its elastic modulus. It can be established that the compressive strength of Plastic Concrete increases with a decrease in the w/c-ratio. Nonetheless, the w/c-ratio does not consider the addition of bentonite, and therefore does not take into account the reduction in free water available for cement hydration. The compressive strength of Plastic Concrete usually lies between 0.5 and 2.5 MPa at 28 days, with the development of compressive strength being quite pronounced, extending significantly beyond the 28-day period. Thus, it may also be advantageous to evaluate the compressive strength of Plastic Concrete at greater ages, such as 56 and 90 days. In addition, the loading rate should be modified to reflect the low strength of the material and should be tested at a loading speed of between 0.02 MPa/s and 0.03 MPa/s.

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The strain at which Plastic Concrete fails is considerably higher than that of conventional concrete, which can reach a maximum strain of 1% when subjected to compression. The hydraulic properties of Plastic Concrete, along with concrete in general, remain a largely under-researched domain, particularly in terms of testing under realistic stress scenarios. It has been demonstrated that the permeability of Plastic Concrete decreases with a lower water-cement (w/c) ratio, which is associated with a less porous material structure. There is limited documentation in the literature regarding the changes in Plastic Concrete permeability over time; however, it has been established that a decrease in permeability over time does occur. Therefore, it is prudent to perform permeability tests on Plastic Concrete at ages greater than 28 days (for example, at 56 and 90 days) to account for the time-dependent variations in permeability.

V. FUTURE SCOPE OF RESEARCH

While these results are promising, there are still questions that need to be addressed, which should inform the objectives of subsequent studies. To begin with, further investigation is required to analyze how the mixing process affects the hardened properties of Plastic Concrete. The emphasis of these studies should be on comprehending the interactions between water, bentonite, and cement, as well as the degree to which varying mixing methods might influence the availability of water during the hydration of cement. Notably, it is imperative to explore reliable analytical methods to effectively characterize bentonite raw materials, as this could provide insights into the mechanisms that dictate the behavior of Plastic Concrete and clarify the requirements for bentonite.

In numerous projects,, the placement of plastic concrete in diaphragm wall panels (ranging in width from 1 to 1.5 m) at higher temperatures has revealed occurrences of bleeding in conjunction with a boiling condition in the upper regions of the panels. This aspect should also be examined from a thermal perspective. Elevated placement temperatures, along with the adiabatic temperature increase resulting from the heat of cement hydration, could contribute to crack development due to thermal behavior, which may adversely impact structural integrity and monolithic action, or may cause excessive seepage and diminish the service life of the structure.

A comprehensive understanding of these mechanisms is also critical for assessing their impact on the compressive and tensile strength of Plastic Concrete, along with its time-dependent properties, including creep and relaxation. Additionally, the creep and relaxation characteristics of Plastic Concrete should be thoroughly investigated, as they significantly affect material stress and consequently influence the design and dimensional stability of cut-off walls. On a different note, the variations in permeability of Plastic Concrete should be a focal point for further research. Greater emphasis on assessing permeability of Plastic Concrete under simultaneous loading conditions could lead to significant discoveries that enhance more realistic design of cut-off walls. To achieve this, the development and validation of a advanced testing approach may also be warranted.

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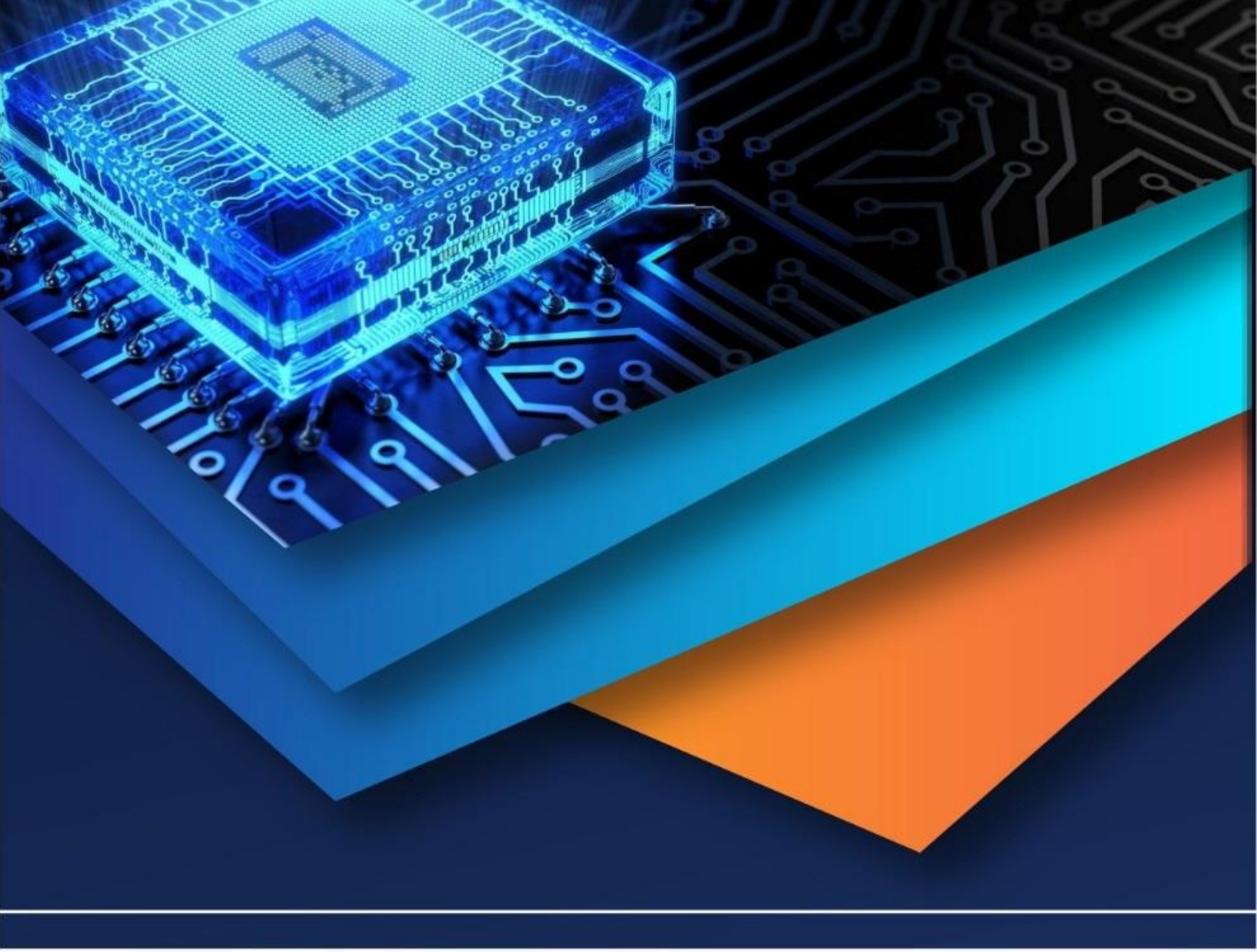
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