# Editorial Board

## Global Journal of Research in Engineering

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Hydraulic Engineering in Dam-Type Tidal Power Plant Designs

By Alexander Yerkhov

Russian State Geological Exploration University

Abstract- During the years of Soviet power, several tidal power plants were procured on the territory of the RSFSR, but only one was built - experimental, despite several promising projects - interest in TPP fell. Economic and demographic trends suggest an impending shortage of energy resources in the world, and now in the foreign press they are increasingly discussing the results of the work of existing TPP, studying the options for the layout of stations, the advantages and disadvantages of various types of hydraulic turbines; the development of the theory of tidal power plants is a problem of energy, construction science (and construction sciences), as well as engineering: hydrology, geology, geodesy, geotechnics, ecology, hydraulics, etc., at each stage of the life cycle of significant in different ways - before the commissioning of the structure in the priority of engineering and construction sciences, and the emphasis in this work is on the main aspect of the life cycle of the design stage, while the scientific novelty is to designate the engineering hydraulics of TPP as a complex problem of system analysis.

Keywords: tide, pool, dam, hydraulic turbine, impeller, blade, power, energy, pressure, operation.

GJRE-E Classification: JEL Code: Q25

Strictly as per the compliance and regulations of:
Hydraulic Engineering in Dam-Type Tidal Power Plant Designs

INЖЕНЕРНАЯ ГИДРАВЛИКА В ПРОЕКТАХ ПРИЛИВНЫХ ЭЛЕКТРОСТАНЦИЙ ПЛОТИННОГО ТИПА

Alexander Yerkhov

Abstract: During the years of Soviet power, several tidal power plants were procured on the territory of the RSFSR, but only one was built - experimental, despite several promising projects - interest in TPP fell. Economic and demographic trends suggest an impending shortage of energy resources in the world, and now in the foreign press they are increasingly discussing the results of the work of existing TPP, studying the options for the layout of stations, the advantages and disadvantages of various types of hydraulic turbines; the development of the theory of tidal power plants is a problem of energy, construction science (and construction sciences), as well as engineering: hydrology, geology, geodesy, geotechnics, ecology, hydraulics, etc., at each stage of the life cycle of significant in different ways - before the commissioning of the structure in the priority of engineering and construction sciences, and the emphasis in this work is on the main aspect of the life cycle of the design stage, while the scientific novelty is to designate the engineering hydraulics of TPP as a complex problem of system analysis.

Keywords: tide, pool, dam, hydraulic turbine, impeller, blade, power, energy, pressure, operation.

Annotation: В годы советской власти на территории РСФСР было запроектировано несколько приливных электростанций, но построена только одна – опытная, несмотря на несколько перспективных проектов, - интерес к ПЭС упал. Экономико-демографические тенденции наводят на мысль о предстоящем дефиците энергоресурсов в мире, и уже сейчас в зарубежной печати всё больше обсуждают результаты работы действующих ПЭС, изучают варианты компоновок станций, достоинства и недостатки разных типов гидротурбин; развитие теории приливных электростанций – проблема энергетики, строительной науки (и строительных наук), а также инженерных: гидрологии, геологии, геодезии, геотехники, экологии, гидравлики и т.д., на каждом этапе жизненного цикла значимых по-разному, – до ввода сооружения в эксплуатацию в приоритете инженерные и строительные науки, и акцент в данной работе делается на основном аспекте жизненного цикла этапа проектирования, научная же новизна – обозначить инженерную гидравлику ПЭС как комплексную проблему системного анализа.

Ключевые слова: прилив, бассейн, плотина, гидротурбина, рабочее колесо, лопасть, мощность, энергия, напор, эксплуатация.

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1. Введение

Ограничение ресурсов по ископаемому топливу и глобальное потепление, вызванное эмиссией парниковых газов ¹, заставляют бедные ресурсами и социально ответственные страны обращаться к альтернативным природным энергетическим источникам: солнечной радиации, ветровым потокам, морским волнам, однако сила их действия носит вероятностный характер, поскольку определяется погодными условиями, – морской прилив предсказуем относительно – наступает периодически два раза в сутки в большинстве регионов и один – в некоторых, при этом суммарная энергия приливов составляет 3 TВт² при КПД преобразования 35 %, что способно удовлетворить часть мирового спроса на электричество, однако, хотя глобальный приливный потенциал значителен, лишь в нескольких районах задействован [1]. Морская энергия заключена не только в приливах в виде потенциальной энергии разных уровней воды, но и в поверхностных волнах ветрового воздействия, а также включает термальную энергию температурных полей различных глубинных зон, – отраслевое значение имеют приливы. Энергию приливам даёт асимметрия гравитационных возмущений и океанические течения: 1) согласно модели Ньютона-Лапласа, линейная гравитация из-за значительного диаметра Земли не одинакова в ближних и дальних точках и неравномерно воздействует на её поверхность, и такое притяжение образует перемещающиеся за движущейся Луной (и Солнцем) горбы и спады поверхности водных масс, которые у материковых берегов создают приливы и отливы; 2) по динамической модели вращение планеты создаёт в океанах обратно-встречные течения из-за возникающего в результате действия силы Кориолиса инерционного движения водных масс, образуя водоворотные зоны

¹ Увеличение выработки электроэнергии в мире более чем в два раза за последние 30 лет с преобладанием доли горючих ископаемых связано исключительно со странами Азии, где наиболее ощутим и ожидаем прогнозируется рост численности населения; за тот же период концентрация диоксида углерода в атмосфере возросла на 25%.
размером, определяемым орографией — береговым и донным рельефом, и поскольку морские берега России воспринимают приливную волну в двух точках — географических регионах: на побережье Баренцева и Белого морей, куда волна доходит от вихря северной части Атлантики, и на протяжённой береговой линии от Берингова до Охотского морей — от двух совместно действующих вихрей Тихого океана, есть только два экономических района РФ — Северный и Дальневосточный, где проектирование ПЭС целесообразно (при условии, что здесь сохранится дефицит электроэнергии при высоком экономическом уровне, и они будут работать в составе единой энергосистемы (рис. 1)). При приливо-отливном движении воды образуется солитон с амплитудой прилива до 6 м на Севере и 13 на Дальнем Востоке, что соответствует низконапорным ГЭС, однако, поскольку сейчас в приоритете атомные проекты, даже низкая себестоимость производства энергии и безопасность для окружающей среды, в сравнении с углеродной энергетикой, не стали аргументом для разработки новых проектов строительства приливных станций. И, казалось бы, в таком контексте, актуальность темы должна определяться выявлением преимуществ сравнения с АЭС (плавучего или иного типа), но важно заглянуть и в будущее, поскольку ископаемое топливо небезгранично, и кризис природных ресурсов станет отправной точкой возврата интереса к ПЭС; мировой нефтяной кризис 1970-х гг. открыл эпоху приливной энергетики, но только сейчас гидротурбины с горизонтальной осью диаметром 5–8 м стали настолько совершенны, что наряду с ветроэнергетическими появились в многочисленных зарубежных проектах ПЭС — и что так не способствует научному обоснованию, как коммерциализации ВИЭ.

Главными достоинствами ПЭС являются низкая стоимость обслуживания — <0,5%, высокая эксплуатационная готовность — >95%; основные недостатки: очень высокая стоимость установленной мощности — в десять-сто раз выше других источников, долгий срок строительства — 5-15 лет, низкий коэффициент загрузки — 22-35% [2], — проблемы инженерно-технического и проектно-технологического характера рассматриваются ниже.

## II. Материалы и Методы

Приливная энергия используется по всему миру, но неравномерно: в Австралии, Великобритании, Канаде, Китае, США, Франции. В РФ проекты экспериментальных ПЭС рассматривали с 1930-х гг., причём Киселогубская опытная малая мощностью 1,7 МВт была построена (в 1968 г. первоначальной мощностью 0,4 МВт); другие проекты не были реализованы [3]: Северная в Баренцевом море, Лубовская и Мезенская в Белом, Пенжинская и Тугурская в Охотском (таблица 1), — на исходе СССР в 1990 г. автор данной статьи в составе солнечногорской исследовательской экспедиции Гидропроекта проводил сейсморазведочные работы по исследованию скального основания под плотину проектируемой ПЭС Северная и геофизические исследования на Шантарских островах под проект Тугурской станции, но случившиеся за этим в стране социально-экономические неурядицы прервали ход работ³; для реализации проектов, помимо главных экономических, должны быть решены частные инженерные задачи.

### Таблица 1: Проекты ПЭС РСФСР

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<th>Станция</th>
<th>Прилив ср. (м)</th>
<th>Площадь бассейна (км²)</th>
<th>Установленная мощность (МВт)</th>
<th>Годовой объем электроэнергии (ТВтч)</th>
<th>Годовой Коэффициент загрузки (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Северная</td>
<td>4,2</td>
<td>5,6</td>
<td>12</td>
<td>0,024</td>
<td>24</td>
</tr>
<tr>
<td>Лубовская</td>
<td>4,2</td>
<td>70</td>
<td>320</td>
<td>0,7</td>
<td>24</td>
</tr>
<tr>
<td>Тугурская</td>
<td>4,7</td>
<td>1800</td>
<td>8000</td>
<td>27,6</td>
<td>24</td>
</tr>
<tr>
<td>Мезенская</td>
<td>10</td>
<td>2640</td>
<td>11400</td>
<td>39</td>
<td>34</td>
</tr>
<tr>
<td>Пенжинская*</td>
<td>11 и 13,4</td>
<td>20530</td>
<td>108500</td>
<td>250</td>
<td>25</td>
</tr>
</tbody>
</table>

*В том же заливе проектировалась Кулойская и Беломорская станции.
**Суммарно два бассейна.

³ И сохранились ли отчёты о результатах изысканий дополнительно не известно: государственные проектные институты распались или переработали, их имущество по большей части ликвидировалось.
Проблема 1 – устойчивость плотины
Безотказность конструкции плотины при постоянных и временных нагрузках определяется силами сопротивления материалов и конструкций, не допускающими предельных состояний: 1) разрушения, потерю устойчивости формы, 2) предельных деформаций, колебаний, трещин и их раскрытия в конструкциях. Расчёт напряжённо-деформированного состояния (НДС) тела плотины при воздействии на неё внешних нагрузок, а также температурных волн и солнечной радиации, химических веществ и соединений в виде действия реакций, определяемых составом внешней среды и изменением свойств частиц конструкций при старении материалов, биологических процессов в виде биодеградации из-за действия грибов, водорослей, микроорганизмов, определяется совокупностью напряжений и деформаций, целиком характеризующих напряжённое состояние части тела плотины, – эту совокупность записывают в виде тензоров напряжений и деформаций конкретной конструкции и решают с применением средств вычислительной техники. Инженерная гидравлика напрямую не связана с методами компьютерного 3-D моделирования НДС численными методами, но ассоциируется с гидростатическими задачами ГТС, при этом в составе расчёта могут использоваться отдельные решения: на сдвиг, напряжений по горизонтальному сечению и т.д.; методику гидростатических расчётов можно применять и для других элементов ГТС ПЭС: подпорных стенок, устоев... Наиболее актуальны и имеют принципиальное значение расчёты по определению устойчивости плотины на сдвиг и напряжения в основании. Исходные данные в расчёте: высота плотины $H_{нм}$ [м], глубина $H$, плотность бетона $γ$ [кт/м$^3$], предел прочности грунта основания [Мпа$^1$], коэффициент трения бетона о грунт $f$, удельное сцепление грунта $c$ [кПа], заложение откосов $m$, класс сооружения [КС]; искомая характеристика – ширина плотины $B$ [м]. Расчёт сил и их плеч ведут относительно середины основания на основе действия группы сил: вертикальных: а) собственный вес плотины, определяемый по площадям плоских геометрических фигур, получаемым разбивкой её поперечного профиля, удельным на плотность бетона, б) составляющие сил гидростатического давления воды, действующий на подводные грани плотины (с обратной стороны на подошву плотины действует сила фильтрационного противодавления – площадь эпюры, умноженная на объёмную массу воды), и горизонтальных: суммарное гидростатическое давление со стороны моря и бассейна (особым вопросом является расчёт флютбета проточной части ПЭС для защиты основания от размыва под действием скоростного напора и предупреждения фильтрационных деформаций, а также наличия и глубины противофильтрационной и дренажной завесы $h_{зав}$). В решении составленного уравнения необходимо учитывать нормативные показатели коэффициентов устойчивости и минимальные значения главных напряжений у верха плотины.

Особенности конструкции плотин ПЭС рассмотрены в следующем разделе.

Рис. 2: Низконапорные гидrotурбины

Проблема 2 – необходимость эффективного управления скоростным напором
Рабочие скорости приливного течения – 2-3 м/с (дают 4-13 кВт/м$^3$), большие (>3,0) оказывают чрезмерную нагрузку на оборудование – на рабочее колесо, меньший напор – экономически неэффективен, – напор определяет тип роторной турбины с характерным рисунком гидродинамического профиля лопатки; применение среднее и высоконапорных требует конструкторских доработок, экономических обоснований. Таким образом, первую проблему можно интерпретировать как создание эффективных, надёжных приливных агрегатов и их совершенствование: 1) турбина Савонюса (рис. 2) с рабочим колесом обычно 2-4 лопасти отличается от колбовой ротором двигателя на внешнем контуре рабочего колеса и статоре в
центре, что имеет преимущества при переменном напоре, дешевле и проще в монтаже и обслуживании\(^4\), теоретически имеет большую инерцию, и, значит, более устойчива, но может работать только в отлив, и не может применяться для накачки\(^5\); 2) в турбине Банки вода ударяет в лопасти, поступая поперечно оси, поворачивает относительно её и выходит, то есть лопасть воспринимает воздействие дважды, эффективность невысока, подходят для небольших станций до 300 кВт, и имеют проблемы с вибрацией; 3) колловую турбину, названную из-за формы гидроагрегата, на ГЭС применяют чаще из-за высокого КПД при низком напоре (до 90%), малого размера, низкой стоимости и реверсивности, позволяющей вырабатывать энергию как в прилив, так и в отлив, они отличаются надёжностью и высокими рабочими характеристиками, имеют низкие эксплуатационные затраты, – технология колловых турбин хорошо отработана; 4) турбины средней скорости вращения\(^6\) (рис. 3) можно адаптировать под различные гидравлические характеристики, однако они малопроизводительны в режиме насоса, потому что относительно короткие лопасти, расположенные под большим углом, создают нестабильное течение и приводят к чрезмерному замедлению потока (что видно по несовпадению рабочих точек режимов турбина/насос), однако конструкция турбины Дериаза, как разновидность Каплана с лопастями не перпендикулярно направленными к оси, а под углом, направляет поток диагонально – по образующей к вершине конуса, и несоответствие между прокачкой и генерацией решает, поскольку не возникают пульсации давления и кавитация\(^4\); турбина/насос Дериаза способна работать также при переменных скоростях вращения, что позволяет иметь в 1,5 раза большую входную мощность, чем у турбины Френсиса; пропеллерная турбина Каплана с возможностью поворота лопасти относительно своей оси ранее (в СССР) называли по конструкции «поворотнолопастной»; 5) высокоопорные (рис. 4) отличаются высокой скоростью при низком расходе: если удельная скорость выходит за критический диапазон, вращение замедляется и мощность падает [5].

\(^4\) Первоначально Кислогубская ПЭС работала на колловой турбине мощностью 400 кВт, но в 2006 г. была модернизирована до экспериментальной ортогональной Савониуса 1,7 МВт (двух агрегата), причём эффективность турбины Савониуса признавается ниже колловой.

\(^5\) Самая большая диаметром 8,2 м и мощностью 17,8 МВт при КПД 89% работает на канадской ПЭС Анаполис (вал. Фандин).

\(^6\) Скорость вращения зависит от удельной скорости гидротурбины, частоты и числа пар полюсов генератора, при этом удельная скорость должна обеспечивать такую же скорость генератора.
Рис. 5: Реактивный и импульсный потоки

Проблема 3 – необходимость выверенной ориентации рабочего колеса турбины в водоводе

Общее наблюдение – вертикальная ориентация вала гидротурбины большого диаметра лучше подходит для реактивных – Каплана, Дериаза, горизонтальное – импульсных – Пелтона (рис. 5); впрочем, изменение формы лопасти по длине – от центра к периферии – способно обеспечивать в одном колесе оба режима, что для требующих повышенных технических характеристик турбин, работающих в составе современного технологического оборудования необходимо. а) Турбины с горизонтальной осью ориентированы валом ротора параллельно потоку, и поскольку, коэффициент их мощности достигает 40%, на большинстве ПЭС установлены именно они, что не означает отсутствия недостатков: стоимость турбины и конструкции выше, ортогональных, генерация энергии возможна только в одном направлении, что требует двух турбинных групп – на прилив и отлив. б) Турбины ортогональные с поперечно ориентированной осью: Банки-Митчелла или Особергера – при простоте конструкции, сказывающейся на стоимости, имеют высокий КПД – 80%, надёжны и просты в эксплуатации; КПД важнейший показатель турбины, в том числе, по признаку ориентации, – турбины с вертикальной осью и, например, пассивным переменным углом напора лопасти для лучшего угла атаки (турбина Кобольда – рис. 6 – может иметь номинальную мощность >150 кВт), удерживающим аэродинамический профиль в положении наибольшей подъёмной силы, обеспечивая максимальную касательную силу для наибольшей мощности, – переменный угол добавляет 3% мощности.

Проблема 4 – неравномерность выработки электроэнергии из-за нерегулярности потока, вызванной длительными паузами прилива/отлива.

Оптимизация путём равномерного распределения выходной мощности (рис. 1) с повышением коэффициента нагрузки турбин выше 60% некоторым образом могут способствовать многоячеистые бассейны, более гибко реагирующие на изменение напора – отбор мощности должен осуществляться от отдельных турбин или их групп, и, таким образом, турбины нижних и верхних бассейнов работают синхронно-циклично по напору – море-бассейн, -бассейн-море, как одна установка; и также станция может доснащаться гидроаккумуляторами.

Рис. 6: Турбина Кобольда

Проблема 5 – недостаточная эффективность преобразования энергии.

Связана со второй проблемой, и решается усовершенствованием конструкции гидротурбины – важно для оптимизации работы станции. Эффективность ПЭС определяется технико-экономическими показателями, то есть минимальными затратами на производство электроэнергии, тогда как КПД турбин – эффективностью в отношении преобразования энергии – зависит от условий работы турбин, и максимальна, если турбина работает с расчётной нагрузкой (рис. 7), – при неполной или перегрузке КПД падает, и рекомендуют турбины Дериаза или Каплана.

Рис. 7: Сравнение некоторых типов турбин. 

Проблема 6 – тяжёлые условия эксплуатации гидротурбин по ряду показателей, например, наличии ила, активно идущих биологических/химических процессов.

Требует изменения свойств материалов или характера процессов путём особых технологических
Природу могущество, а также сужения возможности судоходства, ихтиофауны и т. д. [6]. Проблема 7 – изменение экологического равновесия.

Плотина ПЭС, перекрывающая вход в естественную бухту/залив/фьорд/губу/лиман/эстуарий и даже лагуну, но не пролив, образует бассейн, отделённый от моря, и имеющий различный с ним гидрологический режим (рис. 1), нарушая сложившийся экосистему и в определённых случаях вызывая социальные проблемы, поскольку ограничивается доступ к лежбищам и ареалам обитания держащих у берега морских животных – мlekопитающих, моллюсков и др., изолируются места нереста и пути миграции ихтиофауны, а также сужаются возможности судоходства, – и тем не менее, последствия преодолимы, что должно отражаться в проектах, при этом учитывая надо то, что воздействия на дикую природу могут быть прямыми и косвенными. Проблема 8 – влияние на прибрежно-морской наносный режим и переформирование dna за счёт отложений твёрдого стока рек.

Седиментация уменьшает приливную зону (площадь и объём) бассейна; в зависимости от источника аккумуляция донных отложений и эрозия способны оказать негативное воздействие как на работу сооружений ПЭС, так и на окружающую среду. Эти проблемы с разной степенью важности определяются потоками относительно плотины и в рабочей зоне гидротурбин, – в проектах ПЭС гидравлика сооружений (плотины (потенциальная энергия прилива/отлива), турбинного водовода (кINETическая энергия скоростного напора), а также механических машин (механическая работа гидротурбин)) с вопросами электротехнически взаимосвязана: плотина – главное сооружение ПЭС с решающей долей инвестиционных затрат – имеет в теле на турбинном водоводерабатывающую на перепаде давлений горизонтально или вертикально ориентированную турбину, соединённую посредством вала с коротким и большим в диаметре электрогенератором (рис. 8 [7]), индукцирующим ЭДС, и имеющим, ввиду низкой частоты вращения, несколько пар полюсов, соединённых через трансформатор с сетью. И, следовательно, концепция с анализом и техническое обслуживание с эксплуатацией в жизненном цикле станции имеют приоритетное научно-теоретическое и утилитарно-прикладное значение.
бетона) с соединением элементов сваркой и бетонированием. Положение и форма ячеек сказывается на напряженном состоянии конструкции плотины, что позволяет корректировать напряжения в теле и основании, методом предварительного напряжения повышать сжимающие напряжения у напорных граней. Верхнюю часть такой плотины рассчитывают, как гравитационную, нижнюю — как массивную раму с жёсткими узлами и заделкой в основании.

Помимо экономии бетона, ячеистая плотина имеет ряд других достоинств: удобные цементации швов, сбор и отвод инфильтрационной воды, управление температурным режимом, возможность коммуникации.

b) Решение проблемы 2 — расчёт турбинных агрегатов
1. Энергетический потенциал прилива в исходных данных расчета водовода гидротурбины.

Разница уровней закладывает в приливную волну потенциальную энергию, которая в прилив выходит, чем в отлив, поэтому в оценке приливной энергии следует рассматривать два случая: вращение турбин за счет падающей воды, а поднимающейся. Энергию приливного цикла в работе ПЭС определяют инженерным расчетом по размещению плотины; приняв амплитуду напора на плотину — как разницу уровней Δh (Δh), а площадь бассейна обозначив как A [м²], потенциальную энергию прилива выражают в виде E=mgΔh=2ρgΔh2 [Дж], и мощность приливной энергии — N=ΔEt=2ρgΔh2t [Вт], а если предположить полный переход потенциальной энергии в кинетическую, скорость приливного течения из N=12μ2=12ρμh2 [кг/м²], где Δh — глубина прилива, μ — пройденное приливной волной расстояние в пределах ПЭС, Δt — продолжительность падения или подъема уровня, то есть половина приливной фазы. Вес поднятой и опущенной приливом водой составляет G=μhΔh, где μ — удельный вес морской воды, равный 1025 [кг/м³], и максимальная расчётная мощность ПЭС P=280AH2 [кВт], то есть накопленная энергия пропорциональна квадрату глубины прилива, высоты плотины.

Пример расчёта бассейна Пенжинской ПЭС:
определять теоретическую запасённую энергию и среднюю мощность при средней высоте прилива: 0,5 м на северном и южном бассейнах 12,2 м, площади бассейнов 20 530 000 000 м², а время прилива 6 ч, E = 0,5ρμh2 = 0,5⋅1025 530 000 000 [м²]; 1025 [кг/м³]; 9,8 [м/с²]; 12,2 [м], то есть скорость на входе и выходе 15,3472⋅10⁶ [Дж], P = E/μh = 1,53472⋅10⁶ [Дж]/6 [ч]; 3,6⋅10⁶ [кВт⋅ч/ч] = 710 517 [МВт], при том что плотинные гидрогенераторы по проекту должны производить 108 500 МВт.

Турбина с генератором — наиболее чувствительная критически значимая составляющая ПЭС.

2. Кинетическая энергия турбинного водовода в энергии осевой турбины.

В водоводе, соединяющем море и бассейн, устанавливают турбину, мощность потока в которой Nт=gQHт [кВт], где Hт=12μcos1θ — рабочий напор турбины, позволяет турбине развить мощность Nт=Мо, где M=pQC1cos1R1·C2cos2R2 — момент количеств движения и ω — угловая скорость рабочего колеса, C1, C2 — абсолютные скорости на входе и выходе [м/с], U — окружная скорость на внешней окружности рабочего колеса, ωt = R1, R2 — радиусы окружностей рабочего колеса (рис. 10), а 1, α2 — углы между касательными и кривой линии к наружной окружности на входе и выходе [°], η=NtNп — гидравлический КПД, и в низком напоре турбины с пропеллерными лопастями, как, например, Каплана, не могут обеспечить высокую мощность, Q — расход через гидротехническое сооружение: Q = CdA2gh, где Cd — коэффициент расхода, A — площадь проходного сечения через сооружение.

3. Гидравлические характеристики осевой гидротурбины в конструктивных параметрах мощности.

Сегодня «испытания» концепта начинают с компьютерной модели, выполняя структурный анализ (стандарт ведущим методом конечных элементов – FEA, широко применяемым в расчёте плотин) весовых характеристик конструкции, отдельных деталей и элементов, например, лопастей, и применяя вычислительную гидродинамику (CFD) для оценки набегания и взаимодействия потока с гравитационными поверхностями. Кинематическая характеристика движения потока и рабочего колеса описывается производными физическими величинами передачи скорости потока — скорости на входе лопатки — скорости на выходе — скорости самой лопатки — лопатки, таким образом, определяет диаметр колеса и размер турбины вне зависимости импульсной/реактивной, — лопасти колеса неподвижные, то есть угол их наклона не может изменяться (на рис. 10 показан изогнутая лопасть с входом и выходом струйного потока под заданными
углами, векторно представляющего треугольники скоростей. Чтобы рассчитать крутящий момент, действующий на водяную турбину, необходимо оценить обмен импульсом, то есть обмен импульсом происходит за счёт изменения направления вектора скорости. Мощность турбины определяется силой на входе, скоростью вращения лопастей, выходной мощностью и скоростью потока на выходе. Сила, по второму закону Ньютона – это изменение количества движения \( F=dm\,v\,dt \), то есть определив его получают силы на лопатках. – методика расчёта представляет алгоритм: 1) для расчёта эффективной силы, действующей на лопатки, необходимо рассчитать величину и направление относительной скорости набегающей струи; определение компонент \( x \) и \( y \) вектора относительной скорости на входе: \( vx1=v1\cos, vy1=v1\sin \) и на выходе: \( vx2=v2\cos, vy2=v2\sin\beta \), где \( v1 \) и \( v2 \) – относительные скорости входящего и выходящего потока струи, представляющие сумму векторов скоростей лопасти \( u \) (окружная составляющая стрелы \( u=\pi\cdot d\cdot n \), где \( d \) – диаметр [м], \( n \) – частота вращения [с]); 2) сила, передаваемая реактивным потоком лопатке в направлении \( x \), равна массовому расходу \( Q \) [кг/с], который равен плотности жидкости \( \rho \) [кг/м³] на площадь поперечного сечения стрелы \( A \) [м²] и на скалярное значение скорости набегания \( v \): \( Q=\rho\cdot A\cdot v \); сила, передаваемая реактивным потоком лопатке в направлении оси \( Y \): \( Fy=\rho\cdot A\cdot v\cdot y1=\rho\cdot A\cdot v\cdot\sin +v1\cos; \) полная сила, приложенная к лопатке, равна результатующей: \( F=Fx2+Fy2 \), а угол равнодействующей силы \( \alpha \) =\( \rho\cdot F \); выходная мощность: движущая сила турбины равна \( Fx=\rho\cdot A\cdot v\cdot x1=\rho\cdot A\cdot v\cdot\cos -v\cdot\cos; \) 3) КПД водной турбины – отношение выходной мощности к кинетической энергии движения: \( \eta=\frac{AC\cdot v\cdot x\cdot 2\cdot \cos +v\cdot 1\cdot \cos \cdot u\cdot \cos -v\cdot 1\cdot \cos -u\cdot 2\cdot \cos}{W2} \) и определения угла \( \beta \) (для активных ступеней \( \beta \approx\beta_1 \) – \( (2-4)\)) абсолютной скорость \( C2=W2+u\cdot 2\cdot W2\cdot \cos \) 2 . и а угол \( \alpha_2=2 =\sin 2 \cdot \cos 2 \cdot -u\cdot W2 \).

Рис. 11: Принцип передачи количества движения с решётки на лопасти рабочего колеса

4. Совмещение турбинного водовода со средненапорной гидротурбиной.

Совмещение посредством рабочей (направляющей) решётки – статора, формирующего направленный на лопасти поток как из диффузора (рис. 11), требует отдельного расчёта, и после определения \( C1 \) и \( u \), выбора угла \( \alpha_1 \), вычисляют относительную скорость \( W1 \) на входе в рабочую решётку: \( W1=C12+u2-2\cdot C1\cdot \cos 1 \), и определения угла \( \beta_1 \) по формуле \( 1=\sin 1 \cdot \cos 1 \cdot -u\cdot C1 \), – после оценки относительной скорости на выходе

Рис. 12: Выработка электроэнергии в зависимости от диаметра ротора и скорости потока

Решение проблемы 3 – принципиальное решение по ориентации в потоке рабочего колеса, то есть выбор типа турбины.

Для ПЭС инженерная гидравлика может рассматривать турбины двух типов: а) с горизонтальной осью, ориентированной вдоль потока, диаметром 10-20 м и мощностью 200-700 кВт могут иметь лопасти с регулируемым шагом, подстраиваемым под скорость потока (рис. 12); б) с ортогональной осью и перпендикулярно ей направленным потоком способны извлекать из потока до 35% энергии (для примера, с горизонтальной осью турбины извлекают от 20%); другие преимущества: конструкция низкой материалоёмкости; недостатки: стоимость изготовления на 20% выше турбин со спиральными лопастями (при равной стоимости монтажа), конструкция прямоинейной лопасти (например, вертикальной 3-лопастной турбины Кобольда (рис. 6)) из-за неустойчивости течения с предрасположенностью к разрыву потока приводит к вибрации, но многолетние лабораторные испытания показывают, что геликоидные лопасти турбины Горлова (рис. 2) решают проблему, и кроме того, в сравнении с прямоинейными лопатками, извлекаемая энергия на 12% больше (согласно другим данным коэффициент мощности прямоинейных лопастей на 5% выше спиральных).

Решение проблемы 4 – неравномерность выработки электроэнергии.

Получение электроэнергии ТЭС (рис. 1) при низкой цене на газ является предпочтительной ПЭС как по финансовым, так и техническим соображениям, а также по воздействию на окружающую среду, но КПД ПЭС при мощности 20-250 МВт может быть в 4 раза больше, – важнейшим фактором, снижающим экономическую эффективность ПЭС, являются паузы в работе из-за периodicности приливов/отливов. В традиционном исполнении ПЭС – однобассейное гидroteхническое сооружение с отгораживающей
гидростатического напора, и работа электростанции возможна в трёх режимах: 1) Генерация в прилив; заполнение бассейна морской водой начинается не сразу: некоторое время затворы турбинных водоводов закрыты, пока не возникает достаточный гидростатический напор (в ночное время при низких спросе и тарифе вода пропускается в бассейн через дополнительные отверстия, наполняя его). 2) В отлив при минимальном напоре со стороны моря вода из бассейна выпускается через турбинные водоводы, вырабатывая электроэнергию пока гидростатический напор в бассейне не упадёт до минимального уровня, позволяющего турбинам работать эффективно. 3) Двухнаправленная генерация — метод использует как фазы прилива, так и отлива: затворы турбинных водоводов оставляются закрытыми до конца прилива (рис. 1), после чего воду направляют в турбины — наступает фaza генерации, дающаяся до минимального гидростатического напора – фазы отлива, – двухсторонняя генерация сокращает долю пауз и снижает количество агрегатов, то есть стоимость оборудования. Двухбассейнные ПЭС – основной бассейн может работать как один; второй предназначен для закачки и аккумуляции воды в процессе фазы отлива из первого бассейна, при этом используется часть электроэнергии, генерируемой турбинами, и такая система способна регулировать подачу электроэнергии потребителю, – преимущество систем с двойным бассейном – способность генерировать электроэнергию в период повышенного спроса, недостатки: низкая эффективность работы турбин при низком напоре и увеличение затрат на строительство из-за удлинения плотины. Хотя неравномерность выработки ПЭС не только суточная, но и месячная, но проблема 4 определяется изменением напора в результате приливно-отливного действия волн. Решение проблемы 5 – недостаточная эффективность преобразования энергии и оптимизация – проблема тоже инженерной гидравлики. Экономическая и энергетическая эффективности требуют оптимизации – компьютерного моделирования выработки электроэнергии от изменений уровня воды в бассейне на основе конкретных аналитических подходов, что даёт, прежде всего, оптимальное время начала и окончания генерации каждой фазы. Именно этим является нелинейной зависимостью уровня напора и мощностью определяется проблема возможности выхода станций на проектную мощность. Целью оптимизации эксплуатационных мероприятий является, в первую очередь, определение количества турбин и единых оптимальных эксплуатационных характеристик для одинаково результативной работы во время всех фаз всех приливных циклов. Заданное количество турбин заданной мощности должны обеспечить предполагаемую установленную мощность станции в заданном диапазоне; при моделировании исследуют два режима работы: двухсторонняя генерация без насосных станций и двухсторонняя с накачкой. Для улучшения оперативного управления силовыми установками во времени каждого приливного цикла в качестве исходного параметра применяют одно общее значение, и далее оптимизация моделируемой станции продолжается с последних параметров предыдущего цикла, – последовательность операций по управлению режимами работы ПЭС: 1) откачка воды в отлив (ороножение бассейна), 2) пауза при минимальном уровне отлива (задержка в ожидании), 3) начало прилива (фаза перед наполнением бассейна), 4) начало пропуска воды через затворы, 5) наполнение бассейна, 6) накачка воды в прилив, 7) пауза на максимальном приливном уровне, 8) начало отлива (перед оперожением), 9) пропуск воды в отлив через затворы, 10) откачка воды в отлив (опорожнение бассейна). Эффективная эксплуатация на основе целевой функции каждого цикла максимизирует выход энергии, и добавление прокачки повышает выход электричества на ≈15-20% [8], а в целом оптимизированное управление циклами приводит, за счёт более гибкого управления турбинами и затворами, к увеличению выхода электроэнергии на ≈30-35% (оптимизация повышает КПД модели четырёхлопастной турбины на 5,5 и трёхлопастной на 4,5%). Полностью оптимизированный процесс управления в решении инженерных задач включает большое число переменных (начиная с гидродинамических характеристик прибрежной зоны), требующих повышенных вычислительных ресурсов.
в воде высока из-за наличия в ней растворённых солей – катионов активных металлов: хлоридов и сульфатов натрия, магния, кальция, калия; кроме того, в морской воде высока и диспассивность. Кинетика процессов определяется составом и концентрацией электролита (рис. 13): больше солёность – выше скорость коррозии и ниже надёжность, а также активностью металла конструкции в виде простого вещества или соединения (таблица 2).

Таблица 2: Электрохимический ряд активности металлов

<table>
<thead>
<tr>
<th>Активные</th>
<th>Средней активности</th>
<th>Неактивные</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li → K → Na → Ca → Ba →</td>
<td>Mg → Al → Mn → Zn → Cr → Fe → Ni → Sn → Pb →</td>
<td>H₂ → Cu → Hg → Ag → Pt → Au</td>
</tr>
</tbody>
</table>

К примеру, высокий потенциал медных сплавов в электролитическом контакте со сплавами железа создаёт поток электронов от Fe к Cu, корродируя первый, а это требует специальных методов защиты: легирования, ингибиторов, изолирующих покрытий, электрохимической защиты; выбор метода, предотвращающего окислительно-восстановительную реакцию, определяет стоимость строительства и эксплуатационные издержки.

Сейчас накоплен достаточный опыт работы приливных электростанций, вырабатывающих электричество в сети на протяжении многих десятилетий.

Решение проблемы 7 – воздействие на окружающую среду.

Приливная станция — вредная технология электрогенерации: ПЭС нарушает сложившуюся экосистему географического региона, формируясь в течение тысячелетий, — наиболее показательные примеры с крупными млекопитающими8 в августе 2004 г. на ПЭС Аннаполис в заливе Фанди (рекордные приливы – до 18 м) взрослый горбатый кит в слабый прилив проплыл через открытые ворота шлюза в бассейн, и на несколько дней застрял в верхней части р. Аннаполис, но самостоятельно нашёл выход, однако уже весной 2007 г. там же, у г. Бридкестаун, найдено тело неполовозрелого горбатого кита, и причина гибели осталась неизвестной; впрочем, роль заграждений в данных случаях скорее положительная. ПЭС также могут стать определённой угрозой экономического развития, если в охраняемой зоне активно развито судоходство, но и данная проблема решается при помощи инженерной гидравлики. И вместе с тем, традиционные приливно-отливные электростанции вряд ли будут иметь широкое распространение из-за критических недостатков: дорогоизны, длительного срока строительства, ограниченного числа мест с высоким приливом и подходящей береговой линией, непреодолимой угрозы окружающей среды. Поиск новых технологически совершенных подходов в развитии энергетики формирует в среднесрочной перспективе политику поддержки возобновляемых источников энергии, главным образом солнечных и ветровых, а в долгосрочной — атомных реакторов на быстрых нейтронах (ядерного топлива замкнутого цикла) и ядерного синтеза (термоядерного цикла), а также производства водорода.

Решение проблемы 8 – влияние на прибрежно-морской наносный режим.

Блокирование приливно-отливного течения плотиной способно вызвать увеличение эрозии берегов как со стороны моря, так и бассейна, усилить подводные течения с подмывом сооружений. Инженерная гидравлика открывает широкие возможности в проектировании специальных сооружений, меняющих наносный режим водных объектов: методом лабораторного моделирования участков в пределах акватории можно определять параметры и строить в натуре на дне пороги, на берегах – шоры, то есть возводить простые сооружения, изменяющие сложным образом характер течений, и формирующие отложения твёрдого стока в пределах безопасных и целесообразных, согласно проекту с учётом батиметрических особенностей бассейна.

IV. Заключение

1. Альтернативная энергетика, построенная на возобновляемых источниках, предполагает прекращение в процессе преобразования энергии выработки парниковых газов, – также немаловажным является переориентация поставок ископаемого сырья с энергетического на перерабатывающий промышленный сектор и снижение стоимости получения электроэнергии.

2. Тело плотины ПЭС отлично от устраиваемых на реках и по поперечному профилю, и по конструкционному исполнению, поскольку предназначено для одинаковых с обеих сторон гидростатических напоров, – плотина ПЭС – низконапорная, железобетонная, целесообразна в виде кубоидной формы, ячейстая.

3. Трёхмерные информационные модели потока вдоль турбинных агрегатов позволяют судить о вибрации и кавитации с учётом изменения

8 Исследования – количественные данные о передвижении гиперболических заграждений, выработанные через проекты с учётом ограниченных чисел мест с высокой скоростью приливов и подходящей береговой линией, непреодолимой угрозой окружающей среды. Поиск новых технологически совершенных подходов в...
параметров главных характеристик, например, при большем напоре – меньше вибрация и ниже вероятность возникновения усталости металла; сравнения колебаний сил и моментов, развиваемых в различных турбинных установках, позволяют проектировать конструкции с минимальными колебаниями. Структурный анализ твёрдого тела конструкций гидротурбин позволяет работать на уменьшение колебаний в установках, строительство которых может быть реализовано с использованием механических свойств металла и выбор конструкции.

4. Оптимизация работы ПЭС направлена не только на совершенствование конструкции, но и на использование новых методов. Сравнения колебаний сил и моментов, развиваемых в различных турбинных установках, позволяют проектировать конструкции с минимальными колебаниями. Структурный анализ твёрдого тела конструкций гидротурбин направлен, помимо конструктивной проработки геометрии деталей и основных элементов, таких как форма лопастей, на изучение механических свойств металла и выбор конструкционной стали.

5. Осложнения в эксплуатации, связанные с задачами инженерной гидравлики – волны, ледовые явления, коррозия. Традиционными методами, описанными в СП, рекомендациях, справочниках являются: для снижения силы воздействия волн – волнорезы, берегоукрепление, для ледовых нагрузок – ледорезы, для защиты сороудерживающих решёток от обмерзания – антиобледенители в виде, например, гидрофобных покрытий, для защиты закладных частей затворов – электрообогрева, борьбы с внутренним льдом и шуговыми коврами – запани и шугосбросы. Единым оптимальным решением является использование гидравлического лабораторного моделирования. Для предотвращения электрохимической коррозии металлических конструкций, исполнительных механизмов, деталей турбинных агрегатов в морской воде используют методы: легирования, ингибиторов, изолирующих покрытий, электрохимической защиты.

6. Системный анализ проблем, по сложности сопоставимых с ПЭС, невозможен без колоссальных вычислительных мощностей ЭВМ, поэтому стал широко доступен лишь в последние годы, и целесообразен не только в задачах КИВР, но и в проектах ПЭС, где учтены оптимизация работы турбин, вопросы эксплуатации, охраны водных ресурсов и др.

Литература

Enhancement of Cement’s Compressive Strength of Concrete using Mid-Infrared Ray – A Fundamental Research

By Umakanthan T, Madhu Mathi & Umadevi U

Abstract- Concrete is one of the most versatile material in building construction. Overall quality of cement is indicated by the compressive concrete strength of concrete (CSC). Many techniques are available to increase the CSC. As one of the technology, we irradiated the cement with mid-infrared rays and observed 38% CSC increase. This technology is economical, rapid, easy, user-friendly, can be used by manufacturer to client and in future may gain vast scope and utility in civil engineering.

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GJRE-E Classification: FOR Code: 0905
Enhancement of Cement’s Compressive Strength of Concrete using Mid-Infrared Ray – A Fundamental Research

Umakanthan Tα, Madhu Mathiα & Umadevi Uα

Abstract- Concrete is one of the most versatile material in building construction. Overall quality of cement is indicated by the compressive concrete strength of concrete (CSC). Many techniques are available to increase the CSC. As one of the technology, we irradiated the cement with mid-infrared rays and observed 38% CSC increase. This technology is economical, rapid, easy, user-friendly, can be used by manufacturer to client and in future may gain vast scope and utility in civil engineering.

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I. Introduction

About 10 billion tons of concrete used leading to natural resource decline, and increasing pollution hence research for alternative needed (Liu et al., 2020). Cement price and demand are dynamic. Either saving atleast 1% of cement or increasing the compressive strength of concrete (CSC) would save economy and reduce pollution. CSC is influenced by type and source of cement, supplementary cementitious material and aggregate type (Jared et al., 2022). Through various research CSC was increased upto 72.3% as cited by Liu et al., 2020. Most of these methods are unstable, uneconomical and difficult to follow in field conditions. We successfully tried mid-infrared irradiation and found 38% CSC increase. The effect of mid-infrared in cement’s physic-chemistry is also discussed with various instrumentations.

II. Material and Methods

MIRGA (patent no.: 401387) is a 20 ml pocket sized atomizer (Supplementary file – figure F1) containing inorganic water based solution in which approximately two sextillion cations and three sextillion anions composing Sodium carbonate monohydrate, Sodium carbonate anhydrous, Potassium nitrate and Sodium chloride are present. During spraying, depending on pressure (vary with the user) applied to plunger, every spraying generates 2-6 µm mid-IR. Design of the MIRGA and emission of 2-6 µm mid-IR has been presented in detail by Umakanthan et al., 2022a; Umakanthan et al., 2022b. Every time spraying emits 0.06ml which contains approximately seven quintillion cations and eleven quintillion anions. (details about MIRGA available in supplementary text T1)

The inorganic compounds used in the generation of MIR are a perspective for biomedical applications (Tishkevich et al., 2019; Dukenybayev et al., 2019). It is also a new synthesis method for preparation of functional material (2-6 µm mid-IR) (Kozlovskiy et al., 2021; El-Shater et al., 2022). It is well known that the combination of different compounds, which have excellent electronic properties, leads to new composite materials, which have earned great technological interest in recent years (Kozlovskiy et al., 2021; Almessiere et al., 2022).

Commercial cement and service of an expert panel (n:6) from a local cement manufacturing factory utilized. The spraying was done from 0.25 to 0.5 meter towards any type of packaged (polythene, paper, glass) material (e.g cement bags here) (Method of MIRGA spraying in Supplementary file – video V1). This distance is essential for the MIRGA sprayed solution to form ion clouds, oscillation and 2-6 µm mid-IR generation. The mid-infrared can penetrate the intervening package and act on the cement inside. Close spraying doesn’t generate energy. MIRGA is used like a body spray.

The instruments used to find the changes in,

- Chemical compound transformation – gas chromatography mass spectrometry (GC-MS): Agilent technologies, 7820 GC system, 5977E MSD, Column DB-5, Over temp 100-270°C, Detector MS, Flow rate 1.2, Carrier gas Helium.
- Chemical bond changes – fourier-transform infrared spectroscopy (FTIR): JASCO FT-IR 4200 plus spectrophotometer with ATR (range 4000–400 cm⁻¹ at 298 K); and IR AFFINITY I – FTIR Spectrophotometer, FTIR 7600, Shimadzu.
- Structural changes – powder x-ray diffraction (PXRD): Rigaku RINT 2500 X-ray diffractometer (CuKα anode; λ = 1.541Å). Samples scanned at 40kV and

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30m\(A\) from 5\(^\circ\) to 35\(^\circ\) 20 values and analyzed using PDXL2 software (Rigaku).

Configuration – transmission electron microscopy (TEM): High resolution transmission electron microscopy (HR-TEM) on JEOL (JEM-2100 Plus) system under an acceleration voltage of 200 kV.

Nuclear resonances – Solid state \(^{27}\)Al nuclear magnetic resonance: The experiments were done on a 600 MHz NMR spectrometer (ECZR Series, JEOL, JAPAN) using a 3.2mm CPMAS probe at 150MHz frequency. All the samples were run at 18KHz spinning speed at room temp and with a delay of 5sec.

**a) Method 1**

A commercial bag containing M20 grade 50 kg cement was purchased. From that bag, 1000gms cement was taken, transferred to a polyethene pouch (more than 51 micron thickness) and its opening sealed with cellophane. Similarly, 10 more packets prepared. Among the 11 packets, one was marked as C (Control) and the remaining 10 were individually numbered from 1 to 10. The numbered pouches were respectively given 1 to 10 MIRGA sprayings from 0.25-0.50 meter towards the pouches, at a rate of 1 or 2 on one or either side of the pouches.

Using cement from each of the 11 pouches, a standard weight of ingredients aggregate prepared, cubes of same size were individually casted. Manual casting and compaction of cubes done (pair-form-technique). The cubes were separately cured by submerging in water. Compression tests were conducted with compression testing machine 1000 KN capacity at 7, 14 and 28 days. The trials were conducted in quadruplet and CSC results were compared.

**b) Method 2**

M20 grade 50 kg cement bag was purchased of the same brand and batch as in method 1. 4 samples of 1000 gms each were prepared. One sample was marked as C (Control) and the remaining 3 were numbered 1, 2 and 3. MIRGA salt was added at 0.5%, 0.75% and 1% (w/w) respectively to packets 1, 2 and 3. As in method 1, cubes were prepared, subjected to CSC testing. The trials were conducted in quadruplet and results were compared.

**III. Results and Discussion**

**a) Method 1**

6 and 10 times MIRGA sprayed cement cubes, on 28th day was found to have increased 38-48% CSC respectively compared to control cubes (Table 1).

<table>
<thead>
<tr>
<th>Number of MIRGA spraying</th>
<th>Compressive Strength of Concrete in N/mm(^2) (method 1)</th>
<th>Enhanced percentage of CSC in N/mm(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7(^{\text{th}}) day</td>
<td>14(^{\text{th}}) day</td>
</tr>
<tr>
<td>C (non-sprayed)</td>
<td>13</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
<td>25</td>
</tr>
</tbody>
</table>

6 sprayed: Rough texture, more salty, course, sank very rapidly in water.

| 10 sprayed: Very rough texture, very salty, very course, sank very slowly in water. |

Instrumentation analyses (raw data of instrumentations in Supplementary file – Data D1).

**i. GCMS**

Control: The GCMS profile of the control sample shows peaks at these retention times (min): 12.8, 13.4, 15, 16.3, 17.8, 19.7, ~19.8, ~20, and ~21.8. 2 sprayed sample: There is one additional peak in the 2 sprayed sample at about 18.4 min compared to the control sample GCMS. This additional peak is the marker of different properties of the 2 sprayed sample. 6 sprayed sample: There is an additional apparent peak at about 20.6 min. This change is an indicator of the rough texture, etc. of 6 sprayed sample relative to the control sample. 10 sprayed sample: The peak at ~5.2 min in the GCMS pattern of the 10 sprayed sample does not appear in the GCMS pattern of the control sample or
other samples. This peak is the unique property of the 10 sprayed sample.

Cement sample contains many aldehydes, ketone, short chain alkane & their derivatives. After 2 spraying, there was great increment in peak of dodecane (or its derivatives) while 6 and 10 sprayings and control have not shown this peak. On contrary, 6 and 10 sprayed samples have shown the peak of Cyclohexane (or its derivatives) which was not present in 2 sprayed & control samples. In the sprayed samples, 13-Octadecenal (most abundant peak) was disappeared and converted to various derivatives depending on the number of sprayings. (Fig 1) (Table 2)

Fig. 1: GC-MS of cement samples
### Table 2: GCMS spectra analysis of cement samples

<table>
<thead>
<tr>
<th>R.T. (Min)</th>
<th>Name of Compounds in Cement</th>
<th>% Area presence in Sample</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.809</td>
<td>13-Hexyloxyacloctridec-10-en-2-one</td>
<td>2.17 0.69 1.99 2.29</td>
<td></td>
</tr>
<tr>
<td>16.270</td>
<td>Cyclopentadecanone, 2-hydroxy-</td>
<td>6.60 0.0 0.0 0.0</td>
<td></td>
</tr>
<tr>
<td>16.279</td>
<td>13-Octadeenal, (Z)-</td>
<td>0.0 2.71 0.0 3.15</td>
<td></td>
</tr>
<tr>
<td>16.279</td>
<td>2,3-Dihydroxypropyl elaidate</td>
<td>0.0 0.0 2.93 0.0</td>
<td></td>
</tr>
<tr>
<td>17.839</td>
<td>Cyclopentadecanone, 2-hydroxy-</td>
<td>39.06 0.0 0.0 0.0</td>
<td>Most abundant peak in control sample</td>
</tr>
<tr>
<td>17.839</td>
<td>Cyclohexane, pentyl-</td>
<td>0.0 0.0 37.98 55.15</td>
<td>Most abundant peak in 10 sprayed sample</td>
</tr>
<tr>
<td>19.702</td>
<td>13-Octadeenal, (Z)-</td>
<td>52.70 0.0 0.0 0.0</td>
<td>Most abundant and unique peak in control sample</td>
</tr>
<tr>
<td>19.711</td>
<td>9-Octadecenoic acid (Z)-, 2,3-dihydroxypropyl ester</td>
<td>0.0 0.0 0.0 50.29</td>
<td>Most abundant peak in 10 sprayed sample</td>
</tr>
<tr>
<td>17.849</td>
<td>Dodecan, 2-cyclohexyl-</td>
<td>0.0 49.07 0.0 0.0</td>
<td>Most abundant peak in 2 sprayed sample</td>
</tr>
<tr>
<td>19.712</td>
<td>Cyclopentadecanone, 2-hydroxy</td>
<td>0.0 46.37 61.09 0.0</td>
<td>Most abundant peak in 6 sprayed sample</td>
</tr>
<tr>
<td>19.995</td>
<td>tert-Butyl(5-isopropyl-2-methylphenoxy)dimethylsilane</td>
<td>0.0 7.95 0.0 0.0</td>
<td></td>
</tr>
</tbody>
</table>

**ii. FT-IR**

a. JASCO FT-IR 4200 plus Spectrophotometer with ATR

**Control Sample:** The broad signal in the range 1100-1450 cm⁻¹ is associated with the stretching vibration of Si-OH in the silanol's functional group, although observed in the fingerprint region. Furthermore, in the functional group region, the broad signal in the range 3200-3600 cm⁻¹ is associated with the stretching vibration of O-H.

**2 sprayed Sample:** In the fingerprint region, the broad signal of Si-OH in the range 1100-1450 cm⁻¹ increases significantly. Moreover, in the functional group region, there is a further broadening of O-H in the range 3200-3600 cm⁻¹.

**6 sprayed Sample:** Following the same trend in the 2 sprayed sample, in the fingerprint region, the broad signal of Si-OH in the range 1100-1450 cm⁻¹ continues increasing. Moreover, in the functional group region, the broad signal of O-H in the range 3200-3600 cm⁻¹ increases in value.

**10 sprayed Sample:** In the fingerprint region, the broad signal of Si-OH in the range 1100-1450 cm⁻¹ drops in value. In the functional group region, the broad signal of O-H in the range 3200-3600 cm⁻¹ also drops in value.

The observed changes in the stretching vibrations of Si-OH and O-H can be interpreted as to the 2 sprayed and 6 sprayed samples being more favorable than the control sample, and the 10 sprayed sample being less favourable. At band 1623 cm⁻¹ and 1684 cm⁻¹ bending vibration of water in gypsum seen. At 3554 cm⁻¹ stretching vibration of water in gypsum seen. A broad band at ~ 1650 cm⁻¹ is due to bending vibration of irregularly bound H₂O in 6 and 10 sprayed samples as the rate of hydration is more. (Fig 2)
Cement is a mixture of different compounds. It consists of Calcium oxide (CaO), Silicon dioxide (SiO₂), Aluminum oxide (Al₂O₃), Iron oxide (Fe₂O₃), Water (H₂O), Sulfate (SO₃) and do not have any specific formula. Ca(OH)₂ stretch (present in control sample) indicate Portlandite of cement and it was changed in 2 and 10 sprayed samples, but disappeared in 6 sprayed sample. While 10 sprayed sample showed comparatively increased C-O stretch of [CO₃]²⁻, 2 sprayed sample showed high increment for Si-O stretch. The 6 and 10 sprayed samples uniquely shown asymmetric stretching of Si-O bond while S-O stretching of SO₄²⁻ was selectively present in control and 2 sprayed samples. (Table 3) (Fig 3)

**Table 3: FTIR spectra analysis**

<table>
<thead>
<tr>
<th>Frequency (1/cm)</th>
<th>Band characteristic</th>
<th>% area present in each sample</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3417.86</td>
<td>Portlandite – Ca(OH)₂</td>
<td>1.39 5.34 0.0 0.75</td>
<td>Increase in 2 sprayed sample</td>
</tr>
<tr>
<td>1435.04</td>
<td>C-O stretch of [CO₃]²⁻</td>
<td>13.33 14.06 10.58 21.97</td>
<td>Increase in 10 sprayed sample</td>
</tr>
<tr>
<td>1103.28</td>
<td>S-O stretch of [SO₄]²⁻</td>
<td>6.19 5.17 0.0 0.0</td>
<td>Only present in control and 2 sprayed samples</td>
</tr>
<tr>
<td>1095.57</td>
<td>Si-O (asymmetric stretching)</td>
<td>0.00 0.00 3.5 6.46</td>
<td>Only present in 6 sprayed and 10 sprayed samples</td>
</tr>
<tr>
<td>925.83</td>
<td>Al-O stretch</td>
<td>2.14 2.22 1.44 1.76</td>
<td>Decrease in 6 sprayer and 10 sprayed sample</td>
</tr>
<tr>
<td>455.20</td>
<td>Si-O stretch</td>
<td>2.76 5.34 1.46 2.14</td>
<td>Increase in 2 sprayed sample</td>
</tr>
</tbody>
</table>
iii. **PXRD**

The changes in peak intensities at 11.59° and 29.11° is due to changes in nuclear co-ordinates due to the formation of gypsum and more intense in 6 and 10 sprayed samples. The rate of hydration of the cement is increasing with the increase in the spraying number. The rate of hydration of the cement samples is in the order of control < 2 sprayed < 6 sprayed < 10 sprayed sample. (Table 4) (Fig 4)

**Table 4: PXRD analysis**

<table>
<thead>
<tr>
<th>2θ</th>
<th>Control</th>
<th>2 sprayed</th>
<th>6 sprayed</th>
<th>10 sprayed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>θ</td>
<td>I/Imax %</td>
<td>θ</td>
<td>I/Imax %</td>
</tr>
<tr>
<td>32.24</td>
<td>Alite</td>
<td>3081 100,0</td>
<td>3523 91,9</td>
<td>1911 100,0</td>
</tr>
<tr>
<td>29.48</td>
<td>Alite</td>
<td>2837 92,1</td>
<td>3715 96,9</td>
<td>1576 82,5</td>
</tr>
<tr>
<td>34.42</td>
<td>Ferrite</td>
<td>2582 83,8</td>
<td>2643 69,0</td>
<td>1593 83,4</td>
</tr>
<tr>
<td>26.65</td>
<td>Langbeinite</td>
<td>2418 78,5</td>
<td>3832 100,0</td>
<td>1215 63,6</td>
</tr>
<tr>
<td>51.79</td>
<td>Alite</td>
<td>1903 61,8</td>
<td>1140 29,7</td>
<td>640 33,5</td>
</tr>
<tr>
<td>18.08</td>
<td>Portlandite</td>
<td>1256 40,8</td>
<td>1321 34,5</td>
<td>711 37,2</td>
</tr>
</tbody>
</table>

*Fig. 3: FTIR of cement*
iv. **HR-TEM**

**Control sample:** Mass aggregates show amorphous or ellipsoidal shape, and sizes ranging 0.4 – 1 µm. Most of these appear homogeneously dark. Bands of regularly spaced fringes suggesting Moiré patterns are visible that are typical of crystalline structures. Different particles having typical crystal shapes are visible, namely: triangular particles and needle-like particles. Concerning the triangular particles, it shows two equal-length sides (0.7 µm) and one shorter side (0.4 µm), recalling an isosceles triangle; it also shows bending contours at particle edges, that are typical of crystal torsions. Concerning the needle-like particles, all visible particles have same length, ranging 0.5 – 0.6 µm and show diffraction contrast evidences (including the likely Moiré patterns observed). Both types are thus compatible with crystals. Nanoparticles (average size 20 – 100 nm) are observed with prevalent squared shape and organized in clusters.

**2 sprayed sample:** Mass aggregates of comparable sizes and shapes organized in clusters are observed. Diffraction contrast areas are visible suggesting the presence of crystals. Different from the control, the 2 sprayed sample does not show individual particles with peculiarities typical of crystal, e.g. like those described for the control sample. Given the crystalline nature of this sample, as documented by HRTEM images, small crystals are present here, instead of large ones observed in the control. Moreover, the low frequency by which features typical of crystal structure are observed is coherent with the low frequency of areas of lattice fringe bands observed. Individual nanoparticles similar to those in the control are not visible in the 2 sprayed sample; however, in the aggregate some objects are observed which are comparable to nanoparticles observed in the control.

**6 sprayed sample** has different clusters of mass aggregates showing various shapes and sizes, at
Increasing magnification; a cluster of rectangular crystals and a diffraction pattern image are also shown. Differently from control and 2 sprayed samples, 6 sprayed sample features typical of crystalline structures spread all over the sample mass. This sample is characterized by a large number of crystal structures. Measures of the ring radii in reciprocal lattice unit (1/nm) provide the following interplanar distances (real space, nm): 0.12, 0.16 and 0.20, comparable with measurements performed on bands of lattice fringes. In the diffraction pattern, bright spots are observed uniformly distributed along the rings, indicating that this sample has a polycrystalline texture where crystallites are random oriented; also this finding is coherent with information extracted from the HRTEM image of this sample. Sizes and shapes of mass aggregates are similar to those of control and 2 sprayed samples. However, while in aggregates of these samples diffraction contrast is observed in limited areas of the aggregate, in the 6 sprayed sample signals of diffraction contrast and of Moiré patterns are observed with very high frequency. Moiré patterns are particularly evident. Rectangular and/or squared crystals are also observed with side lengths 0.3 – 0.4 x 0.05 (µm x µm), and 110 – 130 nm respectively.

10 sprayed sample: Similarly to 6 sprayed sample, this sample features typical of crystalline structures in sample mass. This is characterized by a large number of crystal structures. Due to strong overlapping, sizes of individual crystallites are hard to be measured; however they range 50 – 130 nm approx. It has to be noted that, differently from previous samples, crystallites show ellipsoidal shape in the 15-10. Also a small squared crystal is present with side length 40 – 50 nm. Another structure is visible suggesting the presence of overlapped crystals, since dark fringes are observed suggesting diffraction contrast.

In short, degree of crystallinity increased from the control to 6 sprayings. The regularity of crystal structure is enhanced proportionally with increasing spraying from control to 10 sprayings. Concerning the regularity of the crystal structure, instead, an effective improvement is only observed from the 6 and 12 sprayed samples, due to the high degree of crystallinity observed for these two samples. (Fig 5)
v. Solid state $^{27}$Al NMR

Since there is no significant change in the chemical shift and the integral value of the trans-1,2 disubstituted alkene–OCH$_3$ at 130.370 ppm in control, 2, 6 and 10 sprayed samples, we used this peak as a reference to normalize the integral values in all the three data sets. With respect to the control sample, the sulfur compounds at 14.771 ppm and 61.708 ppm drop in the 2 sprayed sample. But in the 6 and 10 sprayed samples theses integrals increase in value again. This behavior is concluded as the 6 and 10 sprayed samples are more favorable than control. (Table 5) (Fig 6)

<table>
<thead>
<tr>
<th>Chemical Shift Description</th>
<th>Control Sample</th>
<th>2 sprayed sample</th>
<th>6 sprayed sample</th>
<th>10 sprayed sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CS</td>
<td>PI</td>
<td>NPI</td>
<td>CS</td>
</tr>
<tr>
<td>Sulfonic and Sulfinic Acids and Derivatives</td>
<td>61.708</td>
<td>8.61</td>
<td>18.30</td>
<td>61.137</td>
</tr>
<tr>
<td>trans-1,2-Disubstituted Alkenes</td>
<td>130.370</td>
<td>0.47</td>
<td>1.00</td>
<td>130.256</td>
</tr>
</tbody>
</table>

CS - Chemical Shift (ppm); PI - Peak Integral; NPI - Normalized Peak Integral
To conclude, the changes in the chemical bonds thereby chemical transformation, configurational changes caused by MIRGA is the cause for inherent characteristic changes in the sprayed cement samples.

c) Future Benefits of Sprayed Cement
- Instead of 1kg of cement (1000 gm), 620 gm of MIRGA sprayed cement (as 38% CSC increased) is enough to achieve regular CSC.
- Economy saved on cements thereby aggregate, water and labour also.
- Production and transport costs reduced.
- Environmental pollution and health hazards reduced.

d) Action of MIRGA Emitted 2-6 µm mid IR on Cement
Invention background, definition, technique of mid-IR generation from MIRGA, toxicological study on MIRGA, safety of the MIRGA sprayed usables and primage and future scope of MIRGA have been described by Umakanthan et al., 2022a (detailed discussion on MIRGA available in supplementary text T2). While spraying MIRGA, most of the mid-IR energy scatters through the air and gets absorbed by cement. Organic compounds absorb mid-IR radiation which causes a change in molecule’s vibrational state to move from the lower ground state to excited higher energy state (Girard, 2014). This leads to changes in cement’s chemical bonds (Shankar, 2017; Mohan, 2004) and these bond parameter changes led to consequent changes in cement’s physical and chemical characters, configuration, compound transformation depending on the dose of mid-infrared applied (Yi, 2012; Esmaeili, 2015; Atkins, 2011; Datta et al., 2014).

As displayed in the results, 2-6 µm MIR generated from the MIRGA equipment caused chemical and molecular level changes in the cement components (photodegradation). In this process, chemical components of the cement have absorbed the MIR and the absorbed MIR photons have altered the chemical bonds of cement molecule; thereby some of the cement molecules are degraded and transformed into another molecule/compound, as reported in GCMS analysis.

Mid-IR has unique vibrational transitions of most molecules (here cement) (Waynant et al., 2011) and has caused various chemical bond stretching and bendings (Mohan, 2004; Agarwal et al., 2014), including new molecule formulation like gypsum formation, crystallinity and hydration (Xu et al., 2017), thus lead to consequent change in physical and chemical properties of cement (Esmaeili, 2015; Datta et al., 2014), hence improved CSC. Mechanical strength of cement mainly comes from accelerated hydration and chemical reaction (Liu et al., 2020) and also refinement of –CH crystal (Wang et al., 2019). The said effects were produced by the mid-infrared as observed in the instrumentation results.

Depending on number of MIRGA spraying (energy given), a receptor’s chemical bond configurations and subsequent physical and chemical characters can be altered to our desire. Such desirable results in coffee, tea, cocoa and edible salts were achieved using MIRGA spraying by Umakanthan et al., 2022a; Umakanthan et al., 2022b; Umakanthan et al., 2023c; Umakanthan et al., 2023d.

Since long, alternative to cement research is ongoing with merits and demerits of the results. CSC improving technologies are use of nanocements (Brown et al., 2019), use of higher strength concrete (40 MPa or 50 MPa) (Jemimah et al., 2021), use of metals waste (Bacelar et al., 2022) and mine drainage sediments, calcium sulfo-aluminate/alkaline hydroxide substances/ aluminosilicate minerals/sodium potassium silicate minerals (Hong et al., 2016). CSC was also increased by various researchers by irradiation with ultraviolet (Bo et al., 2011), microwave (Dmitriev et al., 2017), gamma rays (Osamu et al, 2013), neutron and radiation on sulphur polymer concrete (Piotr et al., 2020), but these are having limitations with application and cost-effectiveness. Far-infrared rays a non-ionizing safe irradiation has also been used in CSC improvement (Fukazawa et al., 1990).

Recently, cement based geopolymer materials are evolved which are technically advantageous. On contrary, cost is high, impracticable in large scale construction and unstable performance (Liu et al., 2020). MIRGA technology can be placed in the literature as one of the CSC improving research.

IV. Conclusion

Mid-IR treated cast cement cubes showed 38% enhanced CSC versus non-treated. Thus, cement quantity could be reduced to 38% less than the usual requirement, saving resources and economy. If the usual quantity of cement is used, 38% more CSC would result. In the authors’ opinion, this study has scope for more fruitful research on cement and its allied materials potentiation, which may result in further economy, reduced transport cost, resource saving and ecological impact.

Author Contribution
Umakanthan: Conceptualization, Methodology, Project administration, Resources, Supervision, Validation.
Madhu Mathi: Data curation, Investigation, Visualization, Writing - Original draft preparation.
Umakanthan, Madhu Mathi: Writing - Reviewing and Editing.

Competing Interest
In accordance with the journal’s policy and our ethical obligation as researchers, we submit that the authors Dr. Umakanthan and Dr. Madhu Mathi are the inventors and patentee of Indian patent for MIRGA.
(under-patent no.: 401387) which is a major material employed in this study.

Data and Materials Availability
All data is available in the manuscript and supplementary materials.

Funding
The authors received no specific funding for this research.

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Enhancement of Cement’s Compressive Strength of Concrete using Mid-Infrared Ray – A Fundamental Research


Supplementary Material

Supplementary data D1: Raw data files of cement instrumentations
https://drive.google.com/open?id=1Q1igeEkD5YHE0TZ-aE99MFBcALmAhMu9

Supplementary video V1: Method of MIRGA spraying
https://drive.google.com/open?id=1QoRwTESKISdoJtfD--xIG9YpTDnVonGW

Supplementary Text T1: Details of MIRGA
MIRGA (patent no.: 401387) is a 20-mL capacity polypropylene plastic atomizer containing an inorganic (molar mass 118.44 g/mole) water-based solution in which approximately two sextillion cations and three sextillion anions are contained. The sprayer unit has dimensions 86 × 55 × 11 mm, an orifice diameter of 0.375 mm, ejection volume 0.062 ± 0.005 mL, and ejection time 0.2 s. The average pressure is 3900 Pa, and the cone liquid back pressure is 2000 N/m² (Supplementary Fig (ii)). During spraying, approximately 1-μg weight of water is lost as mist and the non-volatile material in the sprayed liquid has a concentration of 153 mg/mL. Every time spraying emits 0.06mL which contains approximately seven quintillion cations and eleven quintillion anions.
Depending on the pressure applied to the plunger, every spraying is designed to generate 2–6 µm as estimated by an FTIR (retro-reflector) interferometer instrument (Detector type D* cm HZ1/2 - 1 MCT [2-TE cooled]) at Lightwind, Petaluma, CA, USA.

Supplementary Text T2: Detailed Discussion
1. Detailed discussion [1]
   1.1. Invention background
   The four observable states of matter (solid, liquid, gas, and plasma) are composed of intermolecular and intramolecular bonds. The inherent characteristics of neutrons, protons and electrons are unique, however, differences in their numbers are what constitute different atoms, and how these atoms bind together develops into different molecules with unique characteristics. In the electromagnetic wave (EMW) spectrum, the mid-IR region is vital and interesting for many applications since this region coincides with the internal vibration of most molecules [2]. Almost all thermal radiation on the surface of the Earth lies in the mid-IR region, indeed, 66% of the Sun’s energy we receive is infrared [3] and is absorbed and radiated by all particles on the Earth. At the molecular level, the interaction of mid-IR wavelength energy elicits rotational and vibrational modes (from about 4500–500 cm⁻¹, roughly 2.2 to 20 microns) through a change in the dipole movement, leading to chemical bond alterations [4].

   During our research we have observed: (A) In all objects, even though atoms always remain as atoms, their chemical bond parameters are continuously prone to alteration by cosmic and physical energies (e.g.: EMW, heat, pressure, and humidity) causing the bonds to compress/stretch/bend [5-8], break [9,10], or new bonds to be formed [11]. These alterations ultimately lead to changes in the physicochemical characteristics of the objects. (B) The dynamic, constant, and mutual influences of EMW among the Earth and the celestial and living bodies are continuously causing alterations in the inherent physicochemical characters of earthly objects, for instance, enhancement due to an optimum dose of energy or decrease/destruction due to a high dose of energy (detailed below). Thus, based on these concepts, MIRGA was developed to alter the bond parameters, thereby potentiating the natural characteristics of products.

   1.2. MIRGA definition
   We define MIRGA as ‘a harmless, economical atomizer containing an imbalanced ratio of ions suspended in water, which influence the natural potency of target substances by generating mid-IR while spraying’.

   1.3. Technique of mid-IR generation from MIRGA
   We designed MIRGA as to accommodate an imbalanced ratio of ions suspended in water in their fundamental state, which can move as free particles. The solution exhibits very little detectable background frequency, below even that of cosmic events. By comparison humans emit more radioactivity (around 10 microns) [12,13]. We designed MIRGA to generate energy based on various processes such as: (A) spraying leads to ionization (electrons getting separated from atoms) and many pathways for electron re-absorption; due to these two oscillatory processes, energy is generated; (B) while spraying, a water-based ionic solution gets excited/charged, which in turn leads to oscillation among the imbalanced ions [14] in their excited state, resulting in the emission of photons [15,16]; (C) although a low electromagnetic field exists between the charged particles of the MIRGA’s ionic solution, during spraying the induced oscillation between these charged particles produces energy [17-21]; and (D) in the natural rainfall process, more energy is required to break the water bonds for creating smaller water droplets [22]. Therefore, these droplets should have more stored energy, which then travels down at velocity from a specific distance, thus gaining kinetic energy. When the rain hits the Earth’s surface, it forms a very thin film of mid-IR (near 6 micron), hence there is a net heat gain [22,23]. We simulated this rainfall’s energy-gaining process in MIRGA (i.e., when imbalanced ions in liquid media are atomized, the ejected smaller droplets should have higher internal energy as well as acquired kinetic energy, and the energy emitted by breaking the surface tension). From trial and error, we calibrated the ejection pressure to obtain a desired fine mist, and minimized the evaporation rate by altering the pH and density of the solution. Moreover, the accelerated ions in the sprayed ionic clouds collide among themselves and generate energy [24], thus, we incorporated these phenomena in our atomizer and designed it in such a way as to emit energy in the 2–6 µm mid-IR depending on the given plunger pressure.

   Yousif et al. [25] described this process as a photodissociation of molecules caused by the absorption of photons from sunlight, including those of infrared radiation, visible light, and ultraviolet light, leading to changes in the molecular structure.

1.4. Safety of MIRGA-sprayed products
   In our nearly two-decades of research, we have observed that MIRGA-induced bond-altered target substances do not show any adverse reaction upon consumption/use. In nature, (A) Stereochemical configuration has great influence on taste [26] (e.g., varieties of mango, grapes, rice, etc.), (B) Cooking and digestive enzymes break chemical bonds, thereby softening foods. This indicates that alterations in chemical bonds occur naturally and do not represent a risk to human health. As an example, boiled rice, puffed rice, flat rice, and rice flour have a unique aroma, taste,
texture, and shelf-life but conserving the same molecular formula (C₆H₁₀O₅). (C) In the food industry, sensory attributes and shelf-life are enhanced by altering the food’s chemical bonds using various irradiation processes like radappertization, radicidation, and radurization [27]. (D) Upon heating, water changes from ice to liquid to steam, which are manifestations of changes in the hydrogen bonds [28] but the chemical composition (H₂O) remains the same [29].

1.5. **MIRGA’s primeval and future scope**

The water-based MIRGA could be the first novel potentiating technology. This type of atomizer technology also seems to be present with the extraterrestrials for their therapeutic use during visitations [30].

In various products, we have achieved a range from 30% to 173% potentiation. Even the smaller improvement resulted in 30% monetary and resource savings as well as health benefits. However, there is a knowledge gap between potentiation from 30% to at least 100% for all products, which can be filled-up by refining MIRGA’s ionic solution, concentration, atomizer pressure, and other parameters and even formulating a better solution.

Various mid-IR emitters are now available (e.g., silicon photonic devices [31], cascade lasers quantum and interband [32], non-cascade-based lasers, chalcogenide fiber-based photonic devices [33], and suspended-core tellurium-based chalcogenide fiber photonic devices [34]). These emitters are not as cost-effective as MIRGA and are useful only in astronomy, military, medicine, industry, and research applications. These emitters are too complex for domestic application by the average user.

Because of MIRGA’s wide range of applications, we believe that this technique will resonate in many scientific fields including biophotonics, therapeutics, health, ecology, and others. We are currently conducting research on MIRGA and its applications, namely MIRGA salt, MIRGA vapor and MIRGA plasma.

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Evaluation and Design of Improvement of Al-Jbeiha Signalized Intersection Traffic Operation

By Batool Alaraj & Hana Naghawi

Abstract- The main objective of this paper is to design Al-jubha intersection and the Roadways approaches optimized to better level of service. Traffic design for this intersection include evaluation the current LOS for the intersection and design all possible solutions to reduce congestion, delay and low level of service in this intersection. This design will absolutely save time and money.

An intersection is a shared space that is used by more than one approach at a time. A signalized intersection is one where the shared space is used alternatively by a fixed number of approaches for a predefined time interval as per the phasing scheme used for the intersection.

In this paper, we made unconventional ideas to improve the intersection of the aljabaha signal. the intersection is analyzed as an isolated intersection in this study, using Synchro 8 and HCM 2010 standards. The simulation results the median U-Turn and signal optimization improve the intersection level of service from E-B. The delay for this intersection was reduced to 48.8%, 11.8.

GJRE-E Classification: LCC Code: TA1-2040

Strictly as per the compliance and regulations of:
Evaluation and Design of Improvement of Al-Jbeiha Signalized Intersection Traffic Operation

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1. Introduction

The traffic performance of a roadway network is greatly influenced by the traffic flow through intersections. Many types of traffic control are being used worldwide at intersections such as yield signs, stop signs, roundabouts and signals. Similar to other countries, many traffic signals are installed in Jordan at intersections with moderate and heavy traffic volumes.

Traffic signals ensure safe and efficient traffic flow at intersections, along routes, and in street networks. They improve intersection capacity, minimize traffic delays, enhance safety by reducing specific accidents like right-angle collisions, promote orderly traffic movements, allow safe passage for minor amidst heavy traffic, and aid in establishing a signal system. Transportation professionals primarily measure the performance of signalized intersections based on vehicle delay, a crucial parameter (David 2013).

Vehicle delay is the most important parameter used by transportation professionals in evaluating the performance of a signalized intersection. This is perhaps because it directly relates to the time loss that a vehicle experiences while crossing an intersection (though we have not considered other problems like congestion due to queuing, extra fuel loss due to vehicle ignition etc.) Determining delay at intersections is challenging due to the unpredictable nature of arrival and departure processes. However, extensive research has been conducted to define delay using various analytical models, including deterministic queuing, steady state stochastic, and time dependent stochastic models. These models make assumptions that simplify the complex flow conditions, providing an approximate measure of the average delay experienced by vehicles crossing an intersection. Some studies have also aimed to predict the variance in overall delay for individual vehicles, considering the significant variations and randomness in traffic arrivals and interruptions caused by traffic signal controls (Gupta, 2005).

Vehicles exert a substantial environmental influence through emissions and the consumption of fossil fuels. The burning of gasoline and diesel generates CO2, a greenhouse gas that contributes to climate change. Additionally, vehicles release pollutants like NOx and particulate matter, negatively impacting both air quality and human health. The extraction, refining, and transportation of fossil fuels also lead to habitat destruction and water pollution. To address these issues, there is a strong focus on developing electric vehicles, enhancing fuel efficiency, and investing in alternative transportation options such as public transit and cycling infrastructure. These measures are essential for reducing emissions, improving air quality, and safeguarding the environment for future generations.

a) Project Description

Yajouz road is located in Amman, and it is considered one of the most important dynamic sites which links Amman and Zarqa. In a map is displayed which demonstrates the location of Yajouz road within the districts of Amman.

In this study, a part of the Yajouz road is considered which is Al Jubaiha intersection. The intersection has four legs and connects Yajoz street with Abdullah Al-Lawzi Street. The intersection is signalized, and it is selected because it is considered one of the most important dynamic sites. Jubaiha Intersection has a heavy daily volume of traffic, which leads to a traffic problem represented by delay,
especially during peak hours. It is located in the north of the Jordanian capital.

![Fig. 1: Aljbaha intersection](image)

\[\text{Fig. 1: Aljbaha intersection}\]

\[\text{b) Problem Statement}\]

The increase in road network by widening roads, building new tunnels and other infrastructure is costly and limited by the available spaces in Amman, therefore, the other solution is to decrease the travel demand, especially within the peak hours. The long-term solution requires developing a reliable and comprehensive transportation system and encouraging people to use it instead of private cars. However, the current situation of congested traffic requires immediate solutions with minimal costs, time, and effort. In this project, a micro-scale solution to the delay problem at the intersection is proposed. More than one alternative will be considered (including a signal optimization, median U-Turn and signal optimization with median U-turn), and then the best alternative will be selected. Although, a long-term macro scale solution is required on a network-wide level which considers the interactions between different elements of the roadway. However, the scope of this project is limited to a micro-scale solution.

c) \text{Project Objectives}

This project aims to improve the level of service at Al-Jbeiha intersection. The objectives can be summarized as follows:

1. Assessing the existing level of service at the intersection: Evaluate the current traffic conditions and determine the performance of the intersection.
2. Developing alternative solutions for improved traffic conditions: Propose various strategies and measures that can enhance the traffic flow and alleviate congestion at the intersection. Use simulation models to estimate the resulting level of service for each alternative.
3. Selecting the optimal solution: Analyze and compare the proposed alternatives based on their predicted level of service and feasibility. Determine the best alternative for implementation at the intersection.

\[\text{d) Project Constrains}\]

The main constraints involved in this project are economic and ethical. First, the selected alternative should be economically justified by considering a sequential evaluation process starting from the least disruptive option to the most disruptive option which would be more costly. Furthermore, the design follows all local and international ethical code requirements.

e) \text{Project Standard and Codes}\n
- Highway Capacity Manual (HCM)
- American Association of State Highway and Transportation Officials (AASHTO) 2011

\[\text{II. Literature Review}\]

Hussein (2023) conducted a study to evaluate and enhance four three-leg intersections controlled by STOP signs in various locations within Amman City. The evaluation and improvement processes utilized Highway Capacity Software (HCS-2010) and Synchro-10 software. The validation and simulation were performed using VISSIM-11 software. The evaluation with HCS-2010 and Synchro-10 indicated that the left-turn movements from the minor streets experienced significant delays and operated in a breakdown traffic condition (Level of Service LOS-F). The application of Warrant-3 (Peak Hour Volume) determined that three of the selected intersections warranted signalization under existing conditions, while the fourth intersection did not meet the requirements. For short-term conditions with a growth rate of 5.5%, both software tools indicated that all four selected intersections warranted traffic signals. The optimal cycle length for the traffic signals was determined for each intersection, considering two operation modes for the left-turn movements on the major streets: Protected and Protected-Permitted phase. The HCS-2010 and Synchro-10 software were used for this analysis, and the results were validated using VISSIM-11. The improvements in traffic and geometric conditions resulted in a reduction in vehicle delays, with improved Level of Service (LOS-C or LOS-D) at the minor approaches and the entire selected intersections (LOS-B or LOS-C).

In their study, Khalifate (2021) aimed to improve the capacity and level of service at the sixth circle in Jordan by implementing traffic signals and a roundabout metering approach. The VISSIM software and a C++ program were utilized for this purpose. The sixth circle, situated near Crown Plaza and the Jordan Gate Towers project, experiences congestion due to heavy traffic flow. The study focused on assessing the traffic situation at the sixth circle and proposed potential solutions to reduce daily traffic flow for circle users. In the second scenario, four signals were placed at the roundabout, interconnected with different cycle lengths. A 90-second cycle length resulted in a level of service
The third scenario involved the use of adaptive signals on the roundabout, which were connected to ground detectors placed before the signals. These adaptive signals operated based on the queue length of approaching vehicles detected by the ground detectors. The opening and closing of the signals were designed using simulation and implemented through the C++ programming language.

The first two signals were opened for 45 seconds, prioritizing Swefieh road with reference to King Faisal, and then closed for 45 seconds to open the signal for the next street from the fifth circle, specifically Zahran street.

III. Methodology

The methodology is summarized as follows:

1) Collecting data for the intersection; traffic volumes, geometric components, and traffic signal system.
2) Analysis of the current situation for the intersection, by finding the level of service and delay for the intersection using the Synchro software.
3) Provide solutions for the intersection.
4) Evaluate the performance of the intersection after applying the solutions, in term of level of service and delay, with the help of the Synchro software.

a) Traffic Volumes

Aljbaha intersection located at the Amman, the key traffic data were taken from the department of traffic operations at GAM. Traffic data was collected on April 4th, 2022, with attention to the 15-min peak hour volumes that happened in the morning peak from 7-8 am.

b) Model Development

SYNCHRO8 which is a microscopic level analysis software was used to analyze and evaluate.

i. Current Situation

The current Volumes of the current Volumes values Based on the analysis of data above, the total intersection control delay was found to be 62.1 seconds, under those circumstance the level of service was E. Moreover, the maximum volume to capacity ratio (V/C) was 1.94.

IV. Project Design

The main objective of this paper is to design Al-jubha intersection and the Roadways approaches optimized to better level of service.

Traffic design for this intersection include evaluation the current LOS for the intersection and design all possible solutions to reduce congestion, delay and low level of service using Synchro 8.

a) Signal Optimization: (The FIRST Alternative)

Traffic signal optimization is one of the most cost-effective ways to improve traffic movement and make our streets safe and efficient. Signal optimization is performed for the following reasons: To adjust signal timing to account for changes in traffic patterns due to new developments and traffic growth.

LOS (D) Steady Traffic at High Density. The speed and the maneuverability are severely reduced. Low level of comfort for drivers, as collisions with other vehicles, must constantly be avoided. A slight increase in the traffic risks causing some operational problems and saturating the network.

Under the same phasing and geometric conditions, Synchro 8 results show that the cycle length has decrease to 45 seconds. Furthermore, the total intersection delay has decreased to 48.8 seconds, and the maximum volume to capacity ratio has decrease to 1.8. However, the service level turned into D.
b) Median U-Turn (The Second Alternative)

Median U-Turn: The main disadvantage is the added stopping and delay impact on left turning traffic. Although despite this fact, this design has been shown to improve total intersection delay and travel time conditions under certain volumes. It requires larger R.O.W. along the major roadway. AASHTO recommends a 60ft to accommodate large trucks, from a non-motorized user standpoint, this design presents fewer threats to crossing pedestrians (longer time, refuge area). Level of service LOS (C) Steady Traffic but Limited. The presence of other vehicles affects drivers. The choice of the speed is affected and maneuvering requires vigilance. The level of comfort decreases quickly at this level, because drivers have a growing.

c) Signal Optimization a Median U-turn (Third Alternative)

LOS (B) Steady Traffic: The presence of other vehicles begins to affect the behavior of individual drivers. The choice of the speed is free, but the maneuverability has somewhat decreased. The comfort is excellent, as drivers simply need to keep an eye on nearby vehicles. Intersection delays 11.8s.
V. Results

Table 1: Summary of result

<table>
<thead>
<tr>
<th></th>
<th>Cycle length</th>
<th>Maximum v/c ratio</th>
<th>Intersection delay</th>
<th>Level of service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current situation</td>
<td>158</td>
<td>1.94</td>
<td>62.1</td>
<td>E</td>
</tr>
<tr>
<td>Signal optimization</td>
<td>45</td>
<td>1.3</td>
<td>48.3</td>
<td>D</td>
</tr>
<tr>
<td>Median U-turn</td>
<td>158</td>
<td>0.61</td>
<td>30.5</td>
<td>C</td>
</tr>
<tr>
<td>Signal optimization + Median U-turn</td>
<td>45</td>
<td>0.67</td>
<td>11.8</td>
<td>B</td>
</tr>
</tbody>
</table>

VI. Conclusion

1. The main object of this study is to evaluate the effect of implementing unconventional arterial intersection design.
2. These designs are regarded to be unconventional because they incorporate geometric features or movement restriction that would be accepted at 4 leg intersection.
3. Aljbaha intersection was selected to perform this study. In the final analysis, results showed a different level of improvement according to the UAID model chosen, to sum up, the level of service of Signal optimization, median U-turn and single optimization + median U-turn enhanced from E to D, C, B respectively. Moreover, the intersection delay was reduced by 48.8, 30.5, and 11.8 respectively.
4. Since the median U-turn + single optimization which improved the LOS from E to B on the main intersection the use of median U-turn + single optimization will decrease the delay by 11.8%.

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High Rate Water Clarification Technology

By P. Polasek & C. J. Wantenaar

Abstract- At present the formation of flocculent suspension and its gravity separation are lengthy processes varying between 3 and 4.5 hours. Consequently this results in high capital costs. Therefore, reconsideration of the kinetics of formation of the flocculent suspension and its effect on the gravity separation of formed suspension was needed. This reconsideration revealed that an unconventional, open-minded thinking was required to develop a new water purification technology capable of solving this problem. This technology will most likely be in direct disagreement with the traditional way of thinking in water purification engineering. The reconsideration project also revealed that the current method for the use of water soluble polymers results in a deterioration of the purified water quality and detrimentally affects the operation of filters. Therefore the development of a method for using these polymers, free of side effects, is also essential. A new technology, the High Rate Clarification Technology, combining two processes developed for addressing the above shortcomings, was developed.

Keywords: inline high-density suspension formation process, degree of aggregation, organic agglomeration agent, post-orthokinetic agglomeration, HR clarifier, P-clarifier, POA process.

GJRE-E Classification: DDC: 628.162
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Keywords: inline high-density suspension formation process, degree of aggregation, organic agglomeration agent, post-orthokinetic agglomeration, HR clarifier, P-clarifier, POA process.

I. Introduction

The traditional method for the way of formation of flocculent suspension and its gravity separation are lengthy processes varying between 3 and 4.5 hours. This requires construction of large waterworks on large lands, resulting in higher capital costs. The need to reduce the high capital costs of waterworks received appropriate attention many years ago. This required re-evaluation of the kinetics of formation of flocculent suspension and its effect on the gravity separation. The outcome highlighted the fact that the formation of flocculent suspensions under a commonly low agitation intensity and their gravity separation required an unreasonably long time. This is because the formed aggregates are large, heterogeneous, light in size and of a very low sedimentation velocity. Furthermore, it also showed that the water soluble polymers applied, in accordance to common practice, as coagulant and, or flocculant aids, do not facilitate the formation of rapidly settling aggregates. Instead, they adversely affect both the quality of purified water and the operation of filters by increasing the rate at which filter head-loss rises.

The outcome of the above re-evaluation showed that a non-traditional open-minded thinking was needed to develop a new water purification technology. Such technology that will be able to solve these problems would probably have to be in direct disagreement with the traditional way of thinking in water purification engineering. Such new technology, the High Rate Clarification Technology (HRCT), was developed [1, 2]. It consists of two developed processes, namely the Inline High Density Suspension (IHDS) formation process producing dense micro-aggregates and the Post-Orthokinetic Agglomeration (POA) process agglomerating the micro-aggregates to large, heavy, rapidly settling agglomerates. The impact of HRCT on the acceleration of the sedimentation velocity of formed agglomerates is evident from Figure 1.

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The HRCT has not been described before and is presented now by this article. The principles of High Rate Clarification Technology including the method for the most effective application of water soluble polymers are described under Technological Background. The High Rate clarifiers, incorporating the HRCT, were also developed. The performance results achieved at different localities under different applications are described under the Chapter Design, Operation and Performance of High Rate Clarifiers.

The quality of purified water, to a large extent, is influenced by the type of coagulant used; hydrolyzing coagulants (salts of Al$^{3+}$ and Fe$^{3+}$), if applied under the optimized reaction conditions pertaining to all monitored impurities [3], are capable of purifying water to a quality within the limits defined in the National Standard for drinking water. During this project it was established that the organic coagulants, i.e. water soluble cationic polymers, are not capable of purifying water to the quality attainable by the hydrolyzing coagulants [4-7]. Therefore, the organic coagulants are not an equivalent replacement for the hydrolyzing coagulants.

Particles of impurities consist of two size-fractions, namely the separable and the non-separable particles [8-10]. The total content of particles of impurities is the sum of the content of particles of these two size-fractions. The purpose of water purification is to change the non-separable particles to separable aggregates and then to remove the formed floculent suspension from the water. The total residual concentration of each monitored impurity determines the overall process efficiency attained by the plant; the residual concentration of non-separable particles determines the process efficiency attainable by the technology used.

II. Technological Background

a) Formation of Aggregates

There are two different opinions about the importance of agitation intensity on aggregation. The first traditional opinion commonly accepted across the water purification field is that a low (gentle) agitation intensity is required to form large aggregates. For instance, Han and Lawler [11] described the importance of agitation intensity as follows:

- The importance of the velocity gradient ($G$) has been over-emphasized in the traditional view of aggregation, and $G$ has far less importance than previously thought,
- The velocity gradient $G$, although by no means irrelevant, is relatively unimportant in aggregation.

This means that the agitation intensity actually required is that which is enough to prevent sedimentation of the aggregates being formed.

This opinion is questionable for several reasons. The low agitation intensity is not capable of facilitating continuation of the coagulant dispersion, i.e. the particle destabilization, if this is not completed in the flash mixer. Evidently, the time required to complete coagulation (aggregation) is of no importance. Therefore, the effect of completion of coagulation on the quality of purified water, is also not considered to be of importance.

The aggregates formed by the traditional low agitation intensity ($G < 50 \text{ s}^{-1}$) are heterogeneous and of low density. They are easily affected by extraneous issues like temperature variations, and sun and wind effect. The sedimentation velocity of these aggregates is low and varies over a wide range. Due to this, the sedimentation systems to have an acceptable separation efficiency must be sized for the smallest aggregates required to settle. Therefore, the sedimentation velocity of traditionally designed clarifiers is usually based around $v_s \leq 2 \text{ m.h}^{-1}$.

The other opinion that the agitation intensity is of prime importance in the aggregation is based on Camp [12, 13]. The benefit of high agitation intensity on aggregation in its complexity is described in [1, 14-18].
Understanding the significance of the intensity of agitation on the course of the formation of aggregates and their properties led to the development of the Inline High Density Suspension (IHDS) formation process. The formation of aggregates under the IHDS process produces micro-aggregates fairly uniform in size and density. These micro-aggregates can be enlarged to a lower size macro-aggregates using subsequent low agitation intensity (Figure 2).

Different opinions also exist on the method of using the cationic, anionic and nonionic water soluble organic polymers. A common reason for using these different polymers are their dominant adhesion properties which are capable of facilitating the formation of larger and, therefore, a more rapidly settling suspension.

Technologically these polymers are generally used either as the coagulant aids and, or the aggregation aids and applied into a differently progressed aggregation, or as the aggregation agents (coagulants) replacing the traditional mineral coagulants, primarily the hydrolyzing coagulants. These methods have continued in use for more than 50 years [19-21]. This project proved that the cationic polymers, sometimes referred to as organic coagulants, are not an equivalent replacement for the hydrolyzing coagulants [4, 5, 7, 21].

This project also proved that the commonly accepted method for the use of anionic and non-ionic polymers does not effectively facilitate the formation of larger, and a more rapidly settling suspension. The commonly accepted method does not determine the most effective conditions under which these polymers should be applied to accelerate coagulation-aggregation-sedimentation processes and to most effectively improve the purified water quality.

Furthermore, this common method is considered inappropriate because it also produces certain serious shortcomings and side effects, such as:

- The quality of purified water is poorer than that produced without the polymer,
- The increase in the sedimentation velocity of formed suspension seems to be too low in comparison to the relatively high polymer dosage commonly applied,
- The deep-bed filtration is adversely affected if the filters are not designed for the filtration of a polymer formed suspension. The filtration shortcomings result in a rapid build-up of filter head loss causing the filter bed to operate under undesirable sub-atmospheric pressure, as well as a poorer filter backwashing efficiency, all resulting in the reduced length of the filtration cycle, and the formation of mud-balls; the use of a relatively high polymer dosage used may be one of the major contributors to this problem.

In view of the foregoing the development of a new method for the most effective application of the anionic and non-ionic polymers, became a necessity. This method had to fully utilize the adhesion properties of these polymers, and be free of any detrimental side effects. Therefore, the following aspects of the application of anionic and non-ionic polymers were investigated:

- Significance of the state of aggregation (characterized by the degree of aggregation $\gamma$) reached by the aggregation at the point of addition of polymer on the settling velocity of formed agglomerates and the purified water quality,
- Significance of the electrolyte pH at which these polymers are dissolved on their agglomeration capability,
- Effect of the maturation of the polymer solution on its agglomeration capability,
- Effect of the concentration of the polymer solution on its agglomeration capability,
- Effect of hydrodynamic conditions applied to the dispersal mixing of the polymer solution, i.e. its homogenisation throughout the aggregated water,
- Effect of inline dilution of the polymer concentrated stock solution on its agglomeration potential,

Figure 2: Illustration of the Inline High Density Suspension (IHDS) formation process ($G^* =$ )
• The influence of these polymers on the dosage of the aggregation agent (coagulant).

b) Significance of Velocity Gradient on the Properties of Aggregates

During the aggregation process the destabilized particles combine into primary aggregates. These primary aggregates combine into larger spatial structures and form micro- and macro-aggregates. In these structures, there are lattice spaces filled with water. It is assumed that the total volume of these spaces, as well as the size, structural arrangement and compactness (density) of the aggregates formed are influenced during their formation by the magnitude of adhesion forces and kinetic energy of the colliding particles and the smaller aggregates. This topic is dealt with in [1, 2, 14-16].

i. Size and Shape

This research showed a significant difference in the character and size of aggregates formed by different mean square root velocity gradient $G$. The aggregates formed by a low $G < 50 \text{ s}^{-1}$ are macro-aggregates characterized by an anisotropic shape. The resultant aggregates formed by a higher $G$ become micro-aggregates. The micro-aggregates are more spherical, granular and compact in their structure and of a greater uniformity in size and density than the macro-aggregates. This change in the character of aggregates clearly follows from the mechanism of particles joining into aggregates. The maximum attainable size of aggregates decreases with increasing $G$, and the uniformity in size and compactness of aggregates increases with aggregation time $T$.

ii. Inner structure

During aggregation, the ratio of adhesive and tangential forces influences the arrangement of destabilized particles of impurities in the aggregates and thereby their compactness. The significance of the ratio of these forces on the structure of aggregates being formed can be described as follows: When the adhesive forces are incomparably greater than the tangential forces (low $G$), the particles connect at the point of first contact. The resulting aggregates are large, voluminous and of anisotropic shape; they have a geometrically free, broadly branched, spatial mesh structure. Therefore, they are fragile, with a tendency to fragment. The resulting aggregates contain large volumes of voids filled with water.

In contrast, when the ratio of adhesive and tangential forces is low (high $G$), the primary aggregates in the forming micro-aggregates slide close to one another until they occupy geometrically the most favourable and energetically the most stable position at which they best resist the influence of the applied agitation intensity. Any extension of the agitation time beyond that corresponding to the completion of aggregation does not improve the resultant compactness of aggregates simply because the primary aggregates in the micro-aggregates are already so close to one another that they cannot get any closer. The resultant micro-aggregates are spherical and very compact with a highly arranged inner structure and resistant to fragmentation. These aggregates have the smallest volumes of voids filled with water.

If the tangential forces are considerably greater than the adhesive forces, the formation of aggregates does not occur.

iii. Porosity

Similarity exists between the deposition of primary aggregates in the micro-aggregates and the sand grains in a filtration bed. Both are characterized by porosity. In the case of a filtration bed, the porosity changes according to deposition of the sand grains. In the case of flocculent aggregates, the porosity changes according to the velocity gradient $G$ and time of its duration. Assuming the filter bed consists of spherical grains of the same diameter, Deb [22] described the dependence of the porosity of the filtration bed on the method of deposition as follows: the tangent planes of spherical grains at the point of their contact form a polyhedron. The most free storage of spheres exists when the polyhedron is a cube and the number of contacts is 6; in this case porosity is $\varepsilon_0 = 0.476$. The tightest deposition of these spheres exists when the tangent planes form a twelve-hedron and the number of contacts is 12; in this case porosity is $\varepsilon_0 = 0.2599$.

Furthermore, the micro-aggregates formed at high $G$ and the completion of aggregation were observed to be spherical or close to it. Therefore, the Deb’s model described above can be applied to the deposition of the destabilized particles in the primary aggregates and the primary aggregates in the micro-aggregates.

Compactness of the arrangement of the primary aggregates in the micro-aggregates, i.e. their porosity, changes depending on how close the primary particles are one to another in the micro-aggregates and this is influenced by the magnitude of $G$. Since the porosity of micro-aggregates gradually decreases with an increasing $G$ and $T$ it can be concluded that the attainable porosity can be between $\varepsilon_{\text{max}} = 0.48 - 0.26$ when the most compact micro-aggregates are formed by the IHDS process (Figure 2). Comparison of the porosity of these micro-aggregates with that attainable under the common low intensities of agitation $\varepsilon_{\text{LA}} = 0.80 - 0.93$ [23, 24] shows that a great potential exists for densification of aggregates formed by the IHDS method.

iv. Density

The aggregation produces aggregates of a lower density than that of the particles of impurities from...
which they are formed. While the density of aggregates is low in comparison to that of water, the aggregates are multifold larger than the particles of impurities. Obviously, the density of aggregates is dependent on the relative content of suspended solids in their structure.

Explanation of the significance of agitation conditions on the inner structure of aggregates and consequently their density is evident from the mechanisms of their formation which is dependent on the ratio of adhesion and tangential forces. As described in the foregoing the aggregates formed at low $\overline{G}$ are anisotropic and contain large volumes of water in their voids. Therefore, their porosity is great and hence their density is low. The aggregates formed at high $\overline{G}$ are micro-aggregates that are nearly spherical and very compact. Therefore, they are of low porosity and of great density [14, 15].

c) Two Size Fractions of Particles of Impurities

For the purpose of this article it is necessary to emphasize that the particles of impurities consist of two fractions, separable and non-separable particles. The total content of all particles remaining in the purified water determines the overall quality to which water is purified, while the content of the non-separable particles indicates the best attainable quality limit to which the water can be purified by the technology used, with respect to the particular impurities concerned. Concentration of the non-separable particles is measured in a sample of water after all separable particles are removed by centrifugation taking place under specific conditions [8, 10].

d) Degree of Aggregation

The formation of aggregates in different waterworks takes place under different hydrodynamic conditions and usually ends before the aggregation is completed. Therefore, to assess the state of aggregation achieved before the polymer addition a criterion called the Degree of Aggregation $\gamma$ was developed [1]. It is expressed with sufficient accuracy by the ratio of aggregation achieved at the point of polymer addition, characterized by $\overline{G} T_A$ and $\overline{G} T_{CA}$ at which aggregation is completed. The $\overline{G} T_{CA}$ value is aggregation agent dependent. The Degree of Aggregation $\gamma$ is calculated as follows:

$$\gamma = \frac{\overline{G} T_A}{\overline{G} T_{CA}}$$

were

$\gamma$ - Degree of aggregation (-),
$\overline{G}$ - Mean square root velocity gradient used throughout aggregation (s$^{-1}$),
$T_{CA}$ - Time at which aggregation is completed (s),
$T_A$ - Actual aggregation time - time of aggregation before polymer is applied (s).

The degree of aggregation $\gamma$ permits quantification of the level of aggregation achieved at the time of polymer addition in comparison to completion of aggregation. If $\gamma = 1$ the aggregating system operates under optimized conditions and the best attainable quality of purified water attainable with the coagulant used, is produced. If $\gamma < 1$ the system is under-aggregated; this adversely affects the purified water quality. If $\gamma > 1$ the system is over-aggregated; the purified water quality is not adversely affected but the plant operates uneconomically at a higher power consumption.

III. Classification of Water-Soluble Polymers

The water-soluble polymers can be classified according to their origin, chemical characteristics and applicability as shown in Table 1 [25]. All the polymers used in the purification of water for domestic supply are restricted to a non-toxic quality.

<table>
<thead>
<tr>
<th>ORIGIN</th>
<th>CHEMICAL CHARACTERISTIC</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHEMICALLY TREATED</td>
<td>NATURAL POLYMER</td>
<td>CATIONIC ORGANIC COAGULANT (OC)</td>
</tr>
<tr>
<td>CHEMICALLY UNTREATED</td>
<td>POLYELECTROLYTE</td>
<td>ANIONIC ORGANIC AGGLOMERATION AGENT (OAA)</td>
</tr>
<tr>
<td>SYNTHETIC POLYMERS</td>
<td>NONELECTROLYTE</td>
<td>MIXED ORGANIC FILTRATION AID (OFIA)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NON-IONIC</td>
</tr>
</tbody>
</table>

Table 1: Classification of Polymers used in Water Purification
IV. Materials and Methods

a) Raw Water

The raw water from three different surface sources was used to verify validity of the results obtained. The raw water quality from these water sources is shown in Table 2.

Table 2: The Average Quality of Different Raw Waters used in this Study

<table>
<thead>
<tr>
<th>DETERMINANT</th>
<th>UNITS</th>
<th>LOCH ATHLONE DAM</th>
<th>SAULS.POORT DAM</th>
<th>VAAL DAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>12 - 25</td>
<td>12 – 25</td>
<td>10 - 26</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>7.7</td>
<td>7.4 – 8.2</td>
<td>6.9 – 8.5</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>50 - 690</td>
<td>30 - 250</td>
<td>80 - 225</td>
</tr>
<tr>
<td>Color</td>
<td>mg Pt. L⁻¹</td>
<td>5 – 15</td>
<td>10 - 40</td>
<td>15 - 25</td>
</tr>
<tr>
<td>Total Hardness</td>
<td>mg CaCO₃ L⁻¹</td>
<td>108</td>
<td>90 - 160</td>
<td>37 - 105</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>mg CaCO₃ L⁻¹</td>
<td>75</td>
<td>75 – 140</td>
<td>42 – 110</td>
</tr>
<tr>
<td>COD₅₅</td>
<td>mg O₂ L⁻¹</td>
<td>3.4</td>
<td>6.5</td>
<td>4.0</td>
</tr>
<tr>
<td>THM – potential value</td>
<td>µg CHCl₃ L⁻¹</td>
<td>-</td>
<td>878</td>
<td>-</td>
</tr>
</tbody>
</table>

The performance results achieved by the HRCT purifying water from these three sources were very similar and differed only in their absolute values.

b) Aggregation Agents

The aggregation agents, namely hydrolyzing coagulants such as Fe³⁺ and Al³⁺ salts, and the organic coagulants (cationic polymers) of trade name Floccotan and Superfloc SF-577, were used. Floccotan is a partially condensed product of a commercial wattle tannin extract and treated to produce active amine groups along the polymerized molecule [26]. Superfloc SF-577 is a polyquarternary amine type [27]. Each hydrolyzing coagulant was applied at a dosing rate corresponding to its optimised reaction conditions [3] to remove its cation and water turbidity.

Since the character of the results concerning formation of micro-aggregates, obtained with aggregation agents of both types is very similar, only the results obtained with ferric chloride and Floccotan are presented.

c) Anionic and Non-Ionic Polymers

The anionic and non-ionic polymers are hydrophilic colloids. In water purification, they are used for their dominant adhesive properties. Therefore, the conditions of their optimal application resulting in the formation of large, rapidly settling agglomerates are investigated in this article. The optimal application of these polymers is intended to facilitate the greatest attainable acceleration of the kinetics of sedimentation of formed agglomerates and thereby to reduce the sizes of technological plants and the capital cost of waterworks.

These polymers are of a molecular weight up to 50 million made up of repeating units of a small molecular weight. Each of these repeating units carries one or more ionised groups distributed along the fibrous molecule. A single molecule can be imagined as a longitudinally stretched fiber with a ratio of width to length ranging up to 1:1,000 (the width varies between 0.0003 – 0.0007 μm and the length between 0.4 – 0.8 μm) [28].

The fibrous molecules of these polymers are sensitive to mechanical action and can easily be broken during dissolution, if not handled with care. Therefore, the intensity of mixing applied during polymer dissolving together with the efficiency of dispersal mixing of the dosed polymer solution to achieve its homogenisation with the aggregated water is of significance, as they can considerably affect the agglomeration efficiency of the polymers. These conditions are also dealt with as one of the topics of this article.

Different polyacrylamides available on market under the trade names of Superfloc, Magnafloc, Ultrafloc, BTI, and LTA, were tested. The method of their application is considered correct when the residual turbidity of the purified water produced by the separable and non-separable particles do not exceed the value obtained by the blind test after 60 min sedimentation. Since the character of results obtained with these polymers was practically the same, only the results obtained with the most efficient Superflocs are presented.

The Superflocs provided by Cyanamid Co. of USA (Table 3) were tested, because the branch office supporting service was on the highest professional level. The Superflocs were supplied as powders, emulsions, or solid blocks. Those supplied as emulsions were found to have a very low agglomeration efficiency; therefore, the results obtained are not presented. Those provided in solid blocks are dosed by way of submergence into the stream of water being purified, thus allowing the gradual dissolution of polymer without any meaningful control of its dosage rate. Therefore, only the results obtained with those supplied as powders are presented in this article.
Dissolution of these polymers is a very slow process. It is facilitated by slowly and carefully pouring the polymer powder into the gently agitated electrolyte to prevent the formation of lump clusters, which are difficult to dissolve. Dissolution begins with swelling of macro-molecules. This includes penetration of water molecules into the space between the single layers of polymer, resulting in the formation of a gel-like mass. The single layers expand and disengage. This process is facilitated by mixing at a suitable intensity, preventing breakage of the polymer chains. Mixing should continue until the solution is homogenous and free of "fish eyes". Non-homogenous solutions containing "fish eyes" have a much lower agglomeration efficiency.

Table 3: General Information about the Superflocs Tested [29]

<table>
<thead>
<tr>
<th>Polymer (OAA)</th>
<th>Type</th>
<th>Form</th>
<th>Molecular weight at pH of typical 0.5% solution at 25°C</th>
<th>Contains in %</th>
<th>Recommended dosage [mg.L⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>molecular weight</td>
<td>pH</td>
<td>amide group</td>
</tr>
<tr>
<td>SF 900</td>
<td>N</td>
<td>Powder</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SF 901</td>
<td>N</td>
<td>Powder</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SF 902</td>
<td>N</td>
<td>Powder</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SF-905s</td>
<td>N</td>
<td>Powder</td>
<td>1.5 x 10⁶</td>
<td>5.0</td>
<td>99</td>
</tr>
<tr>
<td>SF 210</td>
<td>A</td>
<td>Powder</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SF 212</td>
<td>A</td>
<td>Powder</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SF A-110</td>
<td>A</td>
<td>Powder</td>
<td>1.0 – 1.2 x 10⁶</td>
<td>-</td>
<td>83</td>
</tr>
<tr>
<td>SF A-130</td>
<td>A</td>
<td>Powder</td>
<td>1.0 – 1.2 x 10⁶</td>
<td>-</td>
<td>68</td>
</tr>
<tr>
<td>SF A-150</td>
<td>A</td>
<td>Powder</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Jar Tests

Jar tests were carried out under the conditions of the IHDS process at G > 50 s⁻¹ until the completion of aggregation γ = 1 (Figure 2).

Two different flocculators were used:

a) Standard Phipp & Bird 6-station flocculator 225, maximum speed 100 RPM, complete with a fully adjustable, variable speed controller common to all 6-stations and a revolution counter,

b) Standard CPI 4-station flocculator, maximum speed 160 RPM, complete with fully adjustable variable speed controller for each station.

The Phipp & Bird flocculator was used in most of the jar tests. The CPI flocculator was only used when the verification of conclusions at a higher stirrer speed was required.

All jar tests used 2-liter standard Pyrex beakers with a 1.5 litre volume of raw water. The stirrer is a double paddle type with a spinning diameter d = 62 mm and a height h = 58 mm.

The effect of the polymers on the quality of purified water was evaluated by residual turbidity produced by both separable and non-separable particles and compared with the blind test. Turbidity produced by both separable and non-separable particles was measured by a Hach 2100A turbidity meter. A Labofuge-1 laboratory centrifuge was used to remove the separable particles from tested samples to determine the content of the non-separable particles in these samples [8-10].

The completion of aggregation of different aggregation agents and the raw waters tested are determined in [1, 13-15].

Depending on the type of test, the jar tests were carried out by one of two modes:

Mode 1: The anionic and non-ionic polymers were applied as an aggregation aid to establish whether or not they functioned as an aggregation aid. The jar tests were carried out as follows: Two sets of six beakers, reaction and service, sited next to one another, were used. The reaction beakers received the same optimised dosage of the same aggregation agent at the same time whereas the polymer solution was dosed into five beakers at different γ = 0.0, 0.25, 0.50, 0.75 and 1.0; the sixth beaker was a blind test. Each reaction beaker was placed into the flocculator and the stirrer was then inserted into each beaker. The set of service beakers, filled with 1.5 litre of raw water is placed next to the reaction beakers. Water from the service beakers was quickly poured into the reaction beakers to disperse and homogenize the aggregation agent throughout the
raw water. The flocculator was switched-on, stirrer speed set up to the maximum RPM and the position of individual beakers adjusted to produce the smallest vortex characterized by the smoothest water surface in each beaker. These operations were completed within a few seconds. The stirrer speed either remained the same or was reduced to the RPM generating the required \( G \). As mentioned in the foregoing, aggregation took place at a high agitation intensity of \( G \geq 50 \text{ s}^{-1} \) over the entire aggregation. The aggregation time was measured from the moment the raw water was poured into the reaction beakers with the polymer dosage applied into the first beaker, \( \gamma = 0 \). As soon as the aggregation time corresponding to \( \gamma = 0.25, 0.50 \) and 0.75, the polymer solution was added to the second, third and fourth beaker respectively. As soon as the aggregation reached its completion, \( \gamma = 1 \), the polymer solution was dosed to the fifth beaker; the flocculator continued to operate at the same speed for another 20 seconds to facilitate homogenization of the polymer solution throughout the aggregated water. After this time the flocculator speed was reduced to an agitation intensity of \( G = 10 \text{ s}^{-1} \) (27 RPM). Agitation continued at this low intensity for 4 minutes to enable agglomerates to fully develop. The polymer’s interaction with progressing aggregation and its influence on the purified water quality and the kinetics of sedimentation of formed agglomerates was evaluated by comparing the changes in the total residual turbidity and turbidity produced by the non-separable particles only, with those measured in the blind test after 60 min sedimentation.

e) Velocity Gradient

The mean square root velocity gradient \( G \) was calculated from the power input transmitted by the stirrer into the water. The power input was measured by torque for different stirrer RPM. The velocity gradient \( G \) was calculated from the averaged values of the torques measured at specific RPM [14]. The conversion of stirrer RPM to velocity gradient \( G \) is in Figure 3.

![Figure 3: Preparation of Anionic and Non-Ionic Polymer Solutions and Homogenization of Dosed Solutions with Aggregated Water](image)

The polymers were dissolved in electrolytes prepared from distilled water, and their pH was adjusted over a wide range using NaOH or HCl. The viscosity of the polymer solutions and pH were measured by an Engler type viscosity meter and a pH meter available at the laboratory used.

Most of the polymer solutions used in the tests were prepared at a concentration \( C = 150 \text{ mg.L}^{-1} \) in a 0.025 N NaOH electrolyte and matured for at least 24 hours, if not stated otherwise.

A magnetic mixer under a gentle mixing was used for polymer dissolution. The mixing intensity was adjusted to prevent breakage of polymer chains. The mixing continued until the solution was clear and free of “fish eyes”, if this was attainable.

Since the characteristics of the dispersal mixing in beakers and clarifiers are very different, only the effect of its duration at the maximum 100 RPM on the agglomeration capability and efficiency, was investigated by jar tests.
V. Results and Discussion

a) Influence of the Achieved Degree of Aggregation $\gamma$ on the Quality of Purified Water and the Kinetics of Sedimentation of Agglomerates Formed

The effect of the anionic polymer applied as aggregation aid and agglomeration agent on the kinetics of sedimentation of formed suspensions and the quality of purified water is shown in Figure 4. Both, the settleability of suspension, and the residual turbidity, improve with increasing $\gamma$-value at which the polymer is applied. The fastest settling velocity and the lowest residual turbidity are achieved when the polymer is applied at the aggregation optimum, $\gamma = 1$. This means that these polymers function as agglomeration agents and not as aggregation aids. The residual turbidity of the settled water did not improve after 10 min. sedimentation.

The individual turbidity readings at 1 min sedimentation shows vast differences in comparison to the blind test (BT). The greatest difference, more than 25-fold, was measured between the readings corresponding to BT and the polymer applied at $\gamma = 1$. This difference indicates the great potential of polymers for accelerating the sedimentation process.

Figure 4: Significance of the $\gamma$-value reached prior to polymer addition on the kinetics of sedimentation of formed agglomerates and residual turbidity of the purified settled water

A similar situation exists regarding the settled water turbidity. The readings after 10 min. sedimentation showed that the lowest residual turbidity produced was achieved by BT, which equals to $\gamma = 1$. It follows from Figure 4 that the higher the $\gamma$-value at which the polymer is dosed the faster the settling agglomerates are formed, producing the lowest residual turbidity of the settled water. Differences in the residual turbidity readings taken at different $\gamma$-values between 1 and 10 minute sedimentation compare as follows:

<table>
<thead>
<tr>
<th>Degree of aggregation $\gamma$</th>
<th>(-)</th>
<th>0.25</th>
<th>0.50</th>
<th>0.75</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differences in turbidity between 1 and 10 min. sedimentation (NTU)</td>
<td>4.4</td>
<td>2.75</td>
<td>1.75</td>
<td>0.9</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The significance of $\gamma$-values at which the polymer is introduced into the aggregating water is also evident by comparing the differences in residual turbidity of the settled water measured after 10 min sedimentation with that of BT (Figure 4). These differences are the result of the polymer’s adverse influence on aggregation efficiency. The differences read as follows:

<table>
<thead>
<tr>
<th>Degree of aggregation $\gamma$</th>
<th>(-)</th>
<th>0.25</th>
<th>0.50</th>
<th>0.75</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differences in total turbidity at 10 min. sedimentation in comparison to the blind test (NTU)</td>
<td>2.6</td>
<td>1.4</td>
<td>0.6</td>
<td>0.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The turbidity produced only by the residual non-separable particles follows the same pattern of separable particles (Figure 5). The highest residual turbidity produced by all particles and the non-separable particles remaining in the purified water exist when the polymer is applied as coagulation aid, $\gamma = 0$. The lowest residual turbidity is produced when the aggregation is completed, $\gamma = 1$, before the polymer addition. This means, the aggregation efficiency and the residual turbidity of purified water produced by both types of particles are not detrimentally affected only when the polymer is applied as an agglomeration agent. Hence, the current method for using these polymers as aggregation aids is unsuitable as it detrimentally affects the purified water quality.
The reasons for the poorer quality of the purified water when an anionic, or non-ionic polymer is applied as aggregation aid, $\gamma < 1$, can be explained by:

a. Interference of the polymers with the destabilization of the particles of impurities that leaves a greater quantity of the non-destabilized, non-separable particles in the purified water.

b. Re-stabilization caused by the polymers of some of the particles of impurities already destabilized but not yet aggregated.

c) Post-Orthokinetic Agglomeration

It is evident from Figures 4 to 6, the anionic and non-ionic polymer, when applied as an aggregation aid, reduces the aggregation capability of the aggregation agent. This detrimental effect is the greatest when the polymer is applied together or shortly after the aggregation agent and decreases as aggregation progresses before polymer addition.

Figures 4 to 6 also show that the best-purified water quality is always produced when the anionic and non-ionic polymers are applied at $\gamma = 1$. This proves that these polymers function as an agglomeration agent (OAA) and not as an aggregation aid as commonly practiced. Therefore, the best results are achieved when aggregation is already completed, $\gamma = 1$, prior to...
polymer addition. This method is called the Post-Orthokinetic Agglomeration (POA) process [1].

It was observed that the POA also improves the strength and resistance to fragmentation of the agglomerates formed.

d) Effect of OAA dosage on the sedimentation kinetics of agglomerates

The effect of different OAA dosing rates on the sedimentation kinetics of agglomerates is illustrated in Figure 7.

Figure 7a shows how the POA process increases the size of the agglomerates and their sedimentation velocity with an increasing OAA dosing rate. The OAA dosing rate \( D_{\text{OAA}} \) varied between 0.01 and 0.1 mg.L\(^{-1}\). At a dosage \( D_{\text{OAA}} \geq 0.03 \) mg.L\(^{-1}\) the agglomerates were already so large that they began to settle during the agglomeration agitation; the higher the OAA dosage the larger and the more rapidly settling agglomerates were formed. It follows from this Figure that the dosing rate of OAA determines the sedimentation velocity of the agglomerates formed.

Figure 7b shows the effect of different OAA dosages on settleability of agglomerates immediately after the flocculator was switched-off and the stirrers removed from the beakers.

Figure 7c shows the effect of different OAA dosages on the character of sludge produced; the consistency of sludge increases with increasing OAA dosage.

e) Significance of Electrolyte Ph on the Agglomeration Capability of OAA

Different OAA were dissolved in electrolytes of different pH to investigate the effect of pH on their agglomeration capability.

<table>
<thead>
<tr>
<th>pH of electrolyte</th>
<th>2.8</th>
<th>4.8</th>
<th>9.0</th>
<th>11.0</th>
<th>12.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH of SF-905s solution</td>
<td>3.0</td>
<td>6.3</td>
<td>7.5</td>
<td>8.2</td>
<td>11.8</td>
</tr>
</tbody>
</table>
The difference between the two readings corresponds to the absorption of single ions from the electrolyte into the polymer macroions. In other words, these differences show the extent to which the electrolyte becomes a donor to the charged groups of the counter ions. This absorption contributes to development of a rodlike configuration of the polyvalent macroions, i.e. the enhancement of the agglomeration potential of OAA.

Similar results were also obtained with the anionic polymers.

f) Effect of the Electrolyte pH on the OAA Solution

During the dissolution of different OAA it was found that their solubility was to a great extent dependent on the electrolyte pH and the brand of OAA (anionic or non-ionic).

Solubility of the anionic polymers increased with an increasing alkaline pH over the full range of pH tested. It was observed that a homogeneous solution free of “fish eyes” was only obtained at a pH > 10; the solution is not homogeneous in the range of pH = 7 to 10. “Fish eye” clusters could not dissolve even after prolonged mixing. The quantity of “fish eye” clusters decreased as the pH increased, and only at a pH > 10 they completely disappeared. For example, the dissolution of SF-A110 at a concentration of \( C = 150 \text{ mg.L}^{-1} \) in a 0.025 N NaOH electrolyte (\( pH \approx 11 \)) to a homogeneous solution free of “fish eyes” was completed in about 4 hours. In an acidic range between a pH = 7 to 4, solubility is so low that the anionic polymers could not dissolve into a homogeneous solution not even during 10 hours dissolving.

Generally, the time required for dissolution of any OAA increases with increasing solution concentration.

All polymers must be dissolved to a clear and homogeneous solution to prevent reduction in their agglomeration capability. For this reason the clarity of electrolyte is very important. The water used for the electrolyte must be soft, or softened to prevent the formation of a precipitate after its alkalization before polymer dissolution. In the event of a precipitate being formed, the agglomeration capability of the polymer solution is considerably reduced.

g) Effect of the Electrolyte pH on the Chemical Structure of OAA

During dissolution the OAA produces either non-ionised molecules or clusters of molecules, or dissociates into polyvalent macroions, polyions, and a great number of single ions of opposite charge, the counter ions. The counter ions of the same charge distributed along the macroion repel each other and this results in the stretching of the fibrous molecule. The macro-molecules in their elongated, rodlike configuration have the greatest agglomeration efficiency while the coil-like macro-molecules have the lowest efficiency. The degree of dissociation, and the stretching of the macro-molecules, is influenced by the electrolyte pH and the concentration of the OAA solution.

The effect of the electrolyte pH on the chemical structure of the macromolecule of polyacrylic acid is explained by Oosawa [28] as follows. With polyacrylic acid the degree of dissociation of the carboxyl group is small in pure water. By adding an alkali (NaOH) the number of negative charges producing Na\(^+\) counter ions increases. The quantity of the added alkali is reflected in the pH value of the solution. Likewise, the chemical structure of the macroions in the solution may be expressed as a copolymer of monomers having COOH\(^-\) and COO\(^-\) groups. At a given pH value and concentration of macroions, the pH value indicates the average proportion of these groups because the solution is a mixture of macroions that have noticeable distributions of two thermally fluctuating groups. When alkali is added on an equimolar basis to the acidic groups, the sodium polyacrylate macroions in the resulting solution are almost entirely dissociated.

The strong charge of the macroions produces a strong electric field, which attracts the counter ions. The charged macroions can assume various random coil configurations over a wide range of extensions, which are dependent on the charge of the environment. In an environment they may take on a rodlike or cylindrical configuration. At low charge densities or in the absence of a charge, the coil configuration can take on a coil-like or spherical configuration. The spherical random coil can have a wide range of apparent radii. For example,
the polyacrylic acid whose degree of polymerization is 1000, takes on a spherical random coil form with a radius of about 200 Å at a low pH. With an increasing pH the macroion extends first spherically and then becomes rodlike, and its resultant length is 2500 Å in its most elongated form. The average local curvature of the chain decreases gradually, as shown below:

![Image](image1.png)

**h) Effect of the Electrolyte pH on the Viscosity of OAA Solutions**

The anionic SF-A110 and non-ionic SF-905s were dissolved at a concentration $C = 150 \text{ mg.L}^{-1}$ in electrolytes of pH varying between 3 and 12. The viscosities of these solutions are plotted in Figure 8.

![Figure 8](image2.png)

**Figure 8:** The effect of electrolyte pH on the OAA solution viscosity

The anionic SF-A110 could not be dissolved in the acidic pH range and, therefore, its viscosity is shown by a dashed line. In the alkaline pH range, the viscosity remained stable up to a pH around 11 and decreased slightly at a pH $> 11.3$. In contrast to that, the viscosity of the non-ionic SF-905s solution remained very steady between pH = 4.3 and 10.8. At a pH $> 11$ it increased slightly, and at a pH $< 4.3$ it decreased slightly. The viscosity measurements were repeated several times. The measured viscosities varied slightly in the absolute values, however the pattern remained the same.

**i) The Effect of pH of OAA Solutions on their Agglomeration Potential**

The influence of the solution pH value for enhancing agglomeration capability of both anionic and non-ionic OAA is evident from the comparison of the sedimentation kinetics in Figures 9 and 10. Figure 9 illustrates the effect of the solution pH of anionic SA-A110, and Figure 10 of the non-ionic SF-905s. The lowest agglomeration capability of the anionic OAA, characterized by the highest residual turbidity (the lowest sedimentation velocity), is reached at pH = 3.2 (Figure 9). At this low pH the configuration of polymer molecules corresponds to their most coil-like spherical configuration. The agglomeration capability gradually improves over the full range of pH tested. The highest agglomeration capability exists at the lowest turbidity (the highest sedimentation velocity) and the highest pH = 12. At this high pH the configuration of polymer molecules corresponds to its most stretched rod-like configuration.

The lowest agglomeration capability of the non-ionic OAA, characterized by the highest residual turbidity (the lowest sedimentation velocity), is reached at around neutral pH = 7 (Figure 10). At this pH the configuration of polymer molecules corresponds to their most coil-like spherical configuration. The agglomeration capability gradually improves in both directions up to the highest pH = 11.5 and the lowest pH = 3.0. The polymer molecules configuration corresponds to their most stretched rod-like configuration at the highest and lowest pH values.
Effect of the Concentration of OAA Stock Solution on the Sedimentation Kinetics

The concentration of the polymer stock solution is also an important factor influencing the agglomeration capability of OAA. The effect of the concentration of OAA stock solution on its agglomeration capability was investigated with the concentrations of 150 mg L\(^{-1}\) and 1500 mg L\(^{-1}\); the stock solution matured for 24 hours. The results obtained with SF-A110 are shown in Figure 11 and can be considered typical for any OAA. These results show that agglomeration capability decreases with increasing concentration of stock solution.

Figure 11 also shows how the inline dilution of the concentrated stock solution is very ineffective. This can be explained as follows: Inline dilution of the concentrated stock solution cannot produce a homogenous solution within the short time available during inline dilution. The diluted solution contains droplets of the concentrated stock solution and the dilution water. Such diluted solution tends to retain the agglomeration efficiency close to the concentration of stock solution. To achieve the same agglomeration efficiency as that attainable with the stock solution of low concentration, a greater OAA dosage is required.

Effect of the Maturation Time of OAA Solution

The effect of maturation (aging) time of OAA solution is yet another factor that was investigated to discover whether it had any effect on the agglomeration efficiency. In this regard, similar results were obtained with both the anionic and non-ionic OAA. The results plotted in Figure 12 were obtained with three SF-A130 solutions of the same concentration but of three different maturation times; one is freshly prepared, the other is 24 hours old and the last one is 30 days old.
The settling curves in Figure 12 show the fresh solution applied immediately after its preparation has the lowest agglomeration efficiency. A significant improvement is achieved when the solution matures for 24 hours before its usage. At a maturation longer than 24 hours the rate of efficiency increase slows down. Therefore, it is advisable to mature OAA solution preferably for 24 hours before its usage. In the event this is not possible then the solution should mature at least for 12 hours before its usage.

Furthermore, it was found that the viscosity of solutions slightly increased with maturation time.

The typical effect of different times of dispersal mixing on the agglomeration efficiency is shown in Figure 13. It follows from this Figure, the sedimentation kinetics of the formed agglomerates improves until the homogenization of OAA solution with the aggregated water is completed. It also shows that the optimum dispersal mixing time peaked at about 20 s as the most rapidly settling agglomerates were formed. Furthermore, it follows from Figure 13 the dispersal mixing lasting longer than the optimum time is less harmful to the efficiency of the POA process than is a shorter time at which homogenization is not yet completed.

It was also established, although the results are not shown, that the time required to complete homogenization depends not only on the intensity of dispersal mixing but also on the concentration of the dosed solution. A longer time is needed for the solution of higher concentration.

(4) Comparison of the Agglomeration Efficiency of Different Kinds of OAA

The agglomeration capability of different anionic and non-ionic OAA is compared in Figures 14 and 15. Figure 14 compares the sedimentation kinetics of different anionic OAA and Figure 15 different non-ionic OAA. The dosage of all OAA was the same, \( D = 0.03 \text{ mg.L}^{-1} \). The most efficient anionic OAA are SF-A110 and SF-A130 and non-ionic OAA is SF-905s, all provided by Cyanamid Co. of USA. The LT-26 provided by the Allied Colloids of UK was found to equal the Superflocs.
Innovations emanating from this project resulted in the development of the High Rate Clarification Technology (HRCT) (Figure 16).

The HRCT combines two processes developed for this purpose, namely:
(a) The Inline High Density Suspension formation process producing dense micro-aggregates,
(b) The Post-Orthokinetic Agglomeration process agglomerating these micro-aggregates to large rapidly settling agglomerates by means of OAA.

The feasibility of all these innovations was verified under long operation of the pilot HR clarifiers and subsequently under the operation of a large capacity plant. The results achieved are presented in the following Chapter.

**VI. Design, Operation and Performance Results of High Rate Clarifiers**

a) **High Rate Clarifiers**

Two types of clarifiers, the High Rate clarifiers incorporating the principles of the HRCT, were developed, namely:

(a) HR clarifier (Figure 17) is a vertical flow type fully fluidized sludge blanket clarifier; this clarifier is particularly suitable for continuous operation under both a steady flowrate, and a relatively slow and gradual fluctuation of the raw water quality,
(b) P-Clarifier (Figure 18) is a radial flow type clarifier with the removal of settled sludge by hydraulic means; this clarifier is suitable for intermittent operation; the formation of micro-aggregates is carried out to completion in a Flocculator installed next to the P-Clarifier.

Three types of suspension can be handled by the High Rate Clarifiers, namely:

a) the conventionally formed floculent suspension,
(b) the micro-aggregates formed by aggregation under the IHDS process,
(c) solid particles up to the finest size contained in the surface water and underground mine water.
i. **HR Clarifier**

The best hydraulically balanced clarifier, the CSAV type [30], incorporating flocculation, a fully fluidized sludge blanket, clarified water and sludge thickening compartments, was converted to the HR Clarifier (Figure 17).

![Figure 17: The HR Clarifier](image)

**From a process point of view, this conversion includes:**

a) Uprating of the aggregation process from taking place under conventional low intensity agitation to the IHDS process taking place at high intensity agitation and completing aggregation ($\gamma = 1$) within the Flocculator and completing it in the Flocculator,

b) Changing the sludge blanket function from continuation of aggregation to the POA process where the micro-aggregates formed in the Flocculator are agglomerated to large, rapidly settling agglomerates by means of OAA (organic agglomeration agent); the OAA are anionic or non-ionic water-soluble polymers.

**Conversion of the CSAV clarifier arrangement involved modification of the Flocculator to incorporate:**

a) Installation of a double-frame, double-anchor, n-tier type stirrer driven by a variable speed drive,

b) Installation of OAA dosing points above the Flocculator bottom and

c) Installation at the Flocculator bottom of a system of deflector baffles to neutralize the rotary motion of the water before entering the sludge blanket compartment.

Raw water containing dispersed coagulant (aggregation agent) discharged from a flash mixer enters the Flocculator. In this compartment, the aggregation takes place under the IHDS process at a high agitation intensity ($\bar{\omega} >>> 50 \text{ s}^{-1}$); the aggregation is completed ($\gamma = 1$) within the Flocculator. The OAA solution is dosed into the Flocculator bottom above the deflector baffles to facilitate its homogenization throughout the aggregated water within the Flocculator before entering the sludge blanket. The deflector baffles neutralize the effect of the rotary motion of water before entering the sludge blanket compartment. The attainable up flow velocity in the sludge blanket, at which the agglomerates are separated, can be varied over a wide range by changing the OAA dosing rate. This is because OAA dosage influences the size of agglomerates formed and their attainable sedimentation velocity. The aggregated water with evenly dispersed OAA enters the conically shaped sludge blanket compartment via an inlet slot. Here, under a low agitation intensity ($\bar{\omega} << 50 \text{ s}^{-1}$), produced by the turbulent fluctuations of the inflowing water, the micro-aggregates are agglomerated to large and rapidly settling agglomerates. No agglomerates are allowed to settle and deposit at the bottom of the sludge blanket compartment as this would facilitate disturbance of the hydraulic balance throughout the sludge blanket compartment and detrimentally affect the clarifier performance. The formed agglomerates are separated from the purified water at the sludge blanket level by continuously draining-off the excess suspension from the sludge blanket level by means of the induced flow into the sludge compartment.

In this compartment the suspension settles and thickens by way of compression. The flow of decanted water from the sludge compartment is combined with the main outlet of purified water discharged from the clarifier. The accumulated sludge is periodically drained-off through the perforated pipe. The sludge compartment is provided with a few sampling pipes to monitor the sludge level and its concentration at different levels. The purified water discharged from the sludge blanket flows through the purified water compartment, where it is evenly collected over the compartment level and discharged from the clarifier at its outlet.

ii. **P-Clarifier**

The P-Clarifier (Figure 18) is a circular, horizontal flow, sedimentation type clarifier, suitable for...
intermittent operation. It incorporates aggregation, sedimentation, purified water and sludge accumulation/thickening compartments. When used as a high rate type, the aggregation takes place to completion in a separate Flocculator installed next to the clarifier. When used for dewatering of thin sludge, the function of the Flocculator changes to the POA process. The sludge compartment is designed to deposit and thicken the settled sludge by compression and to prevent a back-lifting of sludge into the sedimentation compartment during desludging. The sludge is periodically drained-off by hydraulic means through a perforated pipe.

**Figure 18:** P-clarifier

### b) Methods and Procedures

The performance efficiency of the clarifiers was evaluated by changes in the content of the cation (Me) of the Fe$^{3+}$ or Al$^{3+}$ salt, when a hydrolyzing type of aggregation agent was used. Furthermore, changes in natural organic matter (NOM) were measured as COD$_{mn}$, TOC or DOC in both the raw water and the settled water, irrespective of the kind of aggregation agent used.

The total concentration of the specific impurity measured in the raw water is designated by $C_0$, and $C_{CF}$, at the clarifier outlet by $C_C$ and $C_{CF}$, and in the filtrate by $C_F$ and $C_{CF}$. The quantities $C_0$, $C_C$ and $C_F$ mean total concentration of the particular impurity produced by all particles. Abridger $F$ means the content of such impurity is produced only by the non-separable particles. The concentration of non-separable particles $C_{CF}$, $C_{CF}$ and $C_{CF}$ was determined in the tested samples from which the separable particles were removed under specific conditions of centrifugation [8-10].

Turbidity produced by the total content of all particles and the content of non-separable particles was measured by a Hach turbidity meter model 2100A. The concentration of the cation of the aggregation agent was measured colorimetrically by a Bausch & Lomb Spectronic model 70.

The NOM was measured colorimetrically as $C_{\text{OAO}}$ (oxidizability) by oxidation of the organic matter in a boiling mixture of potassium permanganate (KMnO$_4$) and sulphuric acid.

The size distribution of formed aggregates was determined by the Test of Aggregation using a Labofuge 1 laboratory centrifuge. The Test of Aggregation ascribes the aggregates formed to one of the following four basic technological size-fractions, namely: non-aggregated (non-separable) particles (NA), primary aggregates (PR), micro-aggregates (MI) and macro-aggregates (MA). Coagulation efficiency was evaluated by the degree of destabilization $\delta$. The concentration of any type of the monitored impurity is measured by the total concentration of all particles $C$ and by concentration of its non-separable fraction $CF$. The removal of individual impurities was evaluated by the attained $\phi$ and attainable $\phi^*$ separation efficiency [1, 8-10].

The degree of destabilization is the basic criterion of destabilization of the particles of impurities. It is defined as the ratio of the number of particles destabilized in the course of aggregation $N_0$ to the number of aggregately-stable (non-separable) particles in the raw water $N_{NS}$ [8-10].

The aggregation agents, namely ferric chloride and aluminium sulphate (hydrolyzing coagulants) and Floccotan and SF-577 (organic coagulants), were used. These organic coagulants are described under Aggregation Agents.

The OAA used are polyacrylamides, mainly Superflocs SF-110 and SF-A130, provided by the Cyanamid Co. of USA.

### i. Raw Water

The HR clarifiers purified water from three different surface sources. The raw water quality in these sources is summarized in Table 1.
Table 1: Average quality of different raw waters purified by the pilot HR clarifiers

<table>
<thead>
<tr>
<th>DETERMINANT</th>
<th>UNITS</th>
<th>VAAL DAM</th>
<th>LOCH ATHLONE DAM</th>
<th>SAULSPOORT DAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>10 - 26</td>
<td>12-25</td>
<td>12 – 25</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.9 – 8.5</td>
<td>7.7</td>
<td>7.4 – 8.2</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>150 - 200</td>
<td>50 - 690</td>
<td>30 – 250</td>
</tr>
<tr>
<td>Color</td>
<td>mg Pt. L⁻¹</td>
<td>5 – 15</td>
<td></td>
<td>10 – 40</td>
</tr>
<tr>
<td>Total Hardness</td>
<td>mg CaCO₃ L⁻¹</td>
<td>37 - 105</td>
<td>108</td>
<td>90 – 160</td>
</tr>
<tr>
<td>Total alkalinity</td>
<td>mg CaCO₃ L⁻¹</td>
<td>42 – 110</td>
<td>75</td>
<td>75 – 150</td>
</tr>
<tr>
<td>COD₅₇</td>
<td>mg O₂ L⁻¹</td>
<td>4.0</td>
<td>3.4</td>
<td>5.8 – 6.5</td>
</tr>
<tr>
<td>THM – potential value</td>
<td>µg CHCl₃ L⁻¹</td>
<td>-</td>
<td></td>
<td>878</td>
</tr>
</tbody>
</table>

ii. Velocity Gradient

The mean square root velocity gradient $G$ is a parameter ascertaining the average intensity of agitation applied to aggregation. From an operational point of view it is important to evenly distribute the intensity of agitation throughout the Flocculator and to best utilize the retention time in the Flocculator by preventing short circuiting. Hence, great attention has been given to developing a stirrer facilitating these requirements. Such stirrer, a double-frame, double-anchor, n-tier type generating flow in a plane perpendicular to the stirrer shaft, was developed. This stirrer is driven by a variable speed drive thus ensuring the intensity of agitation required to complete aggregation within the Flocculator can be maintained at all times.

![Figure 19: 3 m HR Clarifier - Conversion of Stirrer RPM to Mean Square Root Velocity Gradient $G^*$](image)

The power input, shaft-to-water, was determined from the energy consumed by the stirrer revolving at different revolutions in the Flocculator filled with water, and then again, at the same revolutions when it is empty. The difference between these two power readings is the actual power input, shaft-to-water, dissipated by the stirrer into the water under operating revolutions. From these power inputs, the mean square root velocity gradients $G$ were calculated. Conversion of the stirrer speed to the velocity gradient $G$ is shown in Figure 19.

iii. Concentration of Drained Sludge

The concentration of sludge discharged from the clarifiers was determined as an average concentration established from samples taken either from sludge discharged at the beginning, middle and at the end of desludging, or directly from the samples taken from the sludge compartment at different heights.

VII. Results and Discussion

a) Pilot Hr Clarifiers

Two 3.0 m diameter pilot HR clarifiers were installed at two different localities to demonstrate the potential of the HRCT and to eliminate any doubts about the feasibility of this progressive technology.
The design parameters of the pilot HR clarifiers are as follows [1]:

- Clarifier diameter
- Overall height of the clarifier
- Clarifier volume
- Design capacity (flow rate)

- Agitation intensity during IHDS aggregation process
- Area of the sludge blanket at its separation level
- Design upflow velocity at the sludge blanket level
- Area of separation level in the sludge compartment
- Retention time in the clarifier at the design flow

\[ \begin{align*}
D_C &= 3000 \text{ mm}, \\
H_C &= 4.0 \text{ m}, \\
V_C &= 24 \text{ m}^3, \\
Q &= 21.15 \text{ m}^3\cdot\text{h}^{-1} = 507.60 \text{ m}^3\cdot\text{d}^{-1} \\
\bar{G} &= 100 - 400 \text{ s}^{-1} \\
F_{SB} &= 4.7 \text{ m}^2, \\
V_{UP} &= 4.5 \text{ m}\cdot\text{h}^{-1}, \\
F_{ST} &= 3.0 \text{ m}^2, \\
T_C &= 68 \text{ min}.
\end{align*} \]

b) Installation, Operation and Performance of the First Pilot HR Clarifier

The first pilot HR clarifier was installed at the Rand Water Board Zuikerbosch Waterworks (Figure 20) and operated for about one year during 1970 to 1971. Vaal Dam water was purified (Table 1). Either aluminium sulphate or Floccotan was used as the aggregation agent. The OAA used was SF-A110. It was dissolved at a concentration of 1.0 g.L\(^{-1}\) in 0.025 N NaOH electrolyte prepared from distilled water.

The clarifier performance results were remarkable even though its full potential could not be established due to the low flow rate of the raw water delivery pump.

The clarifier operation and performance capability is summarized as follows [1]:

- Flowrate - limited by the raw water pump capacity
- Upflow velocity at the sludge blanket level:
- Total retention time in the clarifier at the maximum flow
- Raw water turbidity:
- Residual turbidity at the clarifier outlet:

\[ \begin{align*}
Q &= 500 \text{ to } 1150 \text{ m}^3\cdot\text{d}^{-1} \\
V_{UP} &= 4.5 \text{ to } 10.2 \text{ m}\cdot\text{h}^{-1}, \\
T_C &= 30 \text{ min}, \\
C_0 &= 150 \text{ to } 200 \text{ NTU} \\
C_C &= 1 \text{ to } 5 \text{ NTU}
\end{align*} \]

Figure 20: Installation of the pilot HR clarifier at the RWB Zuikerbosch waterworks

c) Installation, Operation and Performance Results of the Second Pilot HR Clarifier

The second pilot HR clarifier (Figure 21) was installed at the municipal waterworks of the City of Bethlehem, Orange Free State, purifying water from the Loch Dam or Saulspoort Dam or a mixture of both (Table 1). This clarifier was operated for seven years during the period of 1974 to 1980 by the waterworks staff. The purified water (on average higher than about 1500 m\(^3\).d\(^{-1}\)) was used to supplement the shortfall in the waterworks capacity.

Aluminium sulphate alternating with Floccotan or Superfloc SF-577 were used as Aggregation agents. SF-A110 was solely used as the OAA; it was dissolved at a concentration of 1.0 g.L\(^{-1}\) in plain tap water because distilled water could not be secured at the daily quantities required. Another OAA, the Allied Colloids LT-25, was also successfully tested, even though for a very short time only. The performance efficiency of both OAA was very similar.

In conformity with the requirements of SABS 241 and common practice in South Africa, the clarifier’s performance was monitored by residual turbidity only. Other determinants, such as the residual concentration of the cation (Me) of the aggregation agent used, and NOM (TOC, DOC, COD\(_{liq}\)) could not be routinely monitored because the waterworks laboratory was not equipped for such analysis.
The raw water to the HR clarifier was delivered by gravity; it was branched off from the delivery pipeline to the waterworks. Depending on the volume of the purified water in the reservoirs, the throughput of the waterworks regularly changed. This often happened during the night hours. As a result, the HR clarifier throughput often changed without warning and consequently without adjustment of the dosing rates and, or intensity of agitation in the Flocculator. Higher residual turbidity in the clarifier outlet is usually a direct consequence of such a situation. Under the optimized operational conditions the residual turbidity at the clarifier outlet did not exceed 5 NTU even at the clarifier’s highest upflow velocities. The higher residual turbidity resulted from $\gamma < 1$ and, or sub-dosages of aggregation agent (producing a poorer quality of purified water) or OAA (resulting in a greater remaining concentration of suspension in the clarifier outlet).

**Figure 21:** Installation of the second pilot HR clarifier at the municipal waterworks of the City of Bethlehem

This HR clarifier performed as follows [1, 31]:
- Flowrate: $Q = 500 - 2877 \text{ m}^3\text{.d}^{-1}$,
- Upflow velocity at the sludge blanket level: $v_{\text{SB}} = 4.5 - 25.5 \text{ m.h}^{-1}$,
- Retention time in the clarifier: $T_C = 68 - 12 \text{ mins}$,
- Clarifier outlet turbidity: $C_C = 2 - 9 \text{ NTU}$,
- IHDS process: $\bar{G} = 100 - 380 \text{ s}^{-1}$,
- Volume of drained sludge: $V_S = 0.245 \% Q$,
- The highest concentration of SS in drained sludge: $C_S = 73.05 \text{ g.L}^{-1}$ (7.305%).

The maximum hydraulic loading $Q = 120 \text{ m}^3\text{.h}^{-1}$, corresponding to an upflow velocity $v_{\text{SB}} = 25.5 \text{ m.h}^{-1}$, which occurred accidentally, as the pressure in the feed pipe to the HR Clarifier increased, due to reduced flow to the waterworks. Under this flowrate the HR clarifier operated as follows: $C_0 = 108 \text{ NTU}$, $C_0F = 58 \text{ NTU}$, $D_{\text{OC}} = 5.94 \text{ mg.L}^{-1}$, $D_{\text{OAA}} = 0.126 \text{ mg SF-A110.L}^{-1}$, $\gamma \approx 0.22$, $C_C \leq 21 \text{ NTU}$, $C_0F \leq 5.2 \text{ NTU}$. The high residual turbidity is the consequence of the system being underdosed, both with the aggregation agent and SF-A110 and being extremely under-aggregated as $\gamma \approx 0.22$. After the agitation intensity and dosages of the aggregation agent and OAA were optimized the performance efficiency improved and returned to its usual level of $C_C < 5 \text{ NTU}$. The total retention time in the clarifier between the point of addition of the aggregation agent and the clarifier outlet was only $T_C = 11.9 \text{ min}$.

d) **Comparison of Performance of the HR Clarifier with Conventional Clarifiers**

The pilot HR clarifier was operated in parallel with three Clariflocculators ($2 \times D = 10.5 \text{ m}$ and $1 \times D = 14.0 \text{ m}$) and a Pretreator clarifier ($D = 18.5 \text{ m}$). The Clariflocculator is a radial flow type sedimentation clarifier with the flocculation compartment sized for about 20 min retention time and a very low intensity mechanical agitation. The Pretreator is a radial flow type sludge blanket clarifier with continuously forced internal sludge recirculation to keep the sludge blanket fluidized.

When comparing performance efficiency, these clarifier systems were operated under the following conditions:

- **Flowrate:**
  - Clarifier: $Q = 500 - 2877 \text{ m}^3\text{.d}^{-1}$
  - Clariflocculator: $Q = 450 - 1800 \text{ m}^3\text{.d}^{-1}$
  - Pretreator: $Q = 4500 \text{ m}^3\text{.d}^{-1}$

- **Upflow velocity at the sludge blanket level:**
  - Clarifier: $v_{\text{SB}} = 4.5 - 25.5 \text{ m.h}^{-1}$
  - Clariflocculator: $v_{\text{SB}} = 2.5 - 5.5 \text{ m.h}^{-1}$
  - Pretreator: $v_{\text{SB}} = 1.5 - 2.5 \text{ m.h}^{-1}$

- **Retention time in the clarifier:**
  - Clarifier: $T_C = 68 - 12 \text{ mins}$
  - Clariflocculator: $T_C = 30 - 90 \text{ mins}$
  - Pretreator: $T_C = 60 \text{ mins}$

- **Clarifier outlet turbidity:**
  - Clarifier: $C_C = 2 - 9 \text{ NTU}$
  - Clariflocculator: $C_C = 1 - 5 \text{ NTU}$
  - Pretreator: $C_C = 2 - 9 \text{ NTU}$

- **IHDS process:**
  - Clarifier: $\bar{G} = 100 - 380 \text{ s}^{-1}$
  - Clariflocculator: $\bar{G} = 200 - 500 \text{ s}^{-1}$
  - Pretreator: $\bar{G} = 100 - 200 \text{ s}^{-1}$

- **Volume of drained sludge:**
  - Clarifier: $V_S = 0.245 \% Q$
  - Clariflocculator: $V_S = 0.2 - 0.5 \% Q$
  - Pretreator: $V_S = 0.2 - 0.5 \% Q$

- **The highest concentration of SS in drained sludge:**
  - Clarifier: $C_S = 73.05 \text{ g.L}^{-1}$
  - Clariflocculator: $C_S = 30 - 70 \text{ g.L}^{-1}$
  - Pretreator: $C_S = 20 - 40 \text{ g.L}^{-1}$

The pilot HR clarifier was found to be more efficient in terms of turbidity removal and sludge production, compared to the other clarifiers.
conditions to produce the same total residual turbidity of the purified water:

- The Clariflocculator (dia 14.0 m) – operated at the design and sedimentation velocity $v_s = 1.2 \text{ m.h}^{-1}$ and retention time of about $T_C = 4$ hours.
- The Pretreator – operated at the design upflow velocity $v_{up} = 1.5 \text{ m.h}^{-1}$ and retention time of about $T_C = 3.5$ hours.
- The HR clarifier – operated at an upflow velocity $v_{up} = 15.5 \text{ m.h}^{-1}$ and retention time of about $T_C = 20$ minutes.

The Clariflocculators and the Pretreator were supplied with water pre-aggregated in a shared hydraulically operated flocculation basin, where aggregation took place under the regular low intensity agitation and a retention time of about 20 mins. The discharge from this basin to the Pretreator was over a hydraulic jump (height of about 600 mm). In the case of the HR clarifier the aggregation agent was dosed into an inline flash mixer installed upstream of the clarifier Flocculator. The IHDS process in the HR clarifier took place with $\varepsilon = 330 \text{ s}^{-1}$.

The waters purified by the HR clarifier and the Clariflocculators were combined and filtered together while the water purified by the Pretreator was filtered in a dedicated filtration plant.

The aluminium sulphate dosage, purifying water to the same total residual turbidity in all three clarifiers, was about 13% lower for the HR clarifier than that applied to the Clariflocculators and Pretreator (Table 2). This proves the importance of the rapid dispersion of the aggregation agent at the flash mixer together with the subsequent high intensity agitation during aggregation facilitating completion of destabilization of particles of impurities and their aggregation.

The performance of these three clarifier systems, evaluated by the Test of Aggregation, is compared in Table 2, and the distribution particle size-fractions is illustrated in Figure 22.

A drop in residual turbidity $C_{CF}$ measured at the outlets of different sections of the clarifier system (Table 2) indicates the extent of the efficient improvement of the purification process. The HR clarifier produced the lowest turbidity $C_{CF} = 1.4 \text{ NTU}$, while the Pretreator was very close to it, $C_{CF} = 1.5 \text{ NTU}$. A considerably higher turbidity was produced by the Clariflocculator, $C_{CF} = 2.9 \text{ NTU}$. The relatively high $C_{C}$ and $C_{CF}$ values at the outlet from the HR clarifier are due to a 13% lower dosage of the aggregation agent than the optimum applied to the other clarifiers. The low $C_{CF}$ value of the Pretreator in comparison to the Clariflocculators was partly due to the hydraulic jump at the end of pre-aggregation enhancing destabilization of impurities and partly due to the enhancing effect of the sludge blanket. Undoubtedly, the highest $C_{CF}$ value produced by the Clariflocculator proves that a low agitation intensity applied to the aggregation process does not favourably affect enhancement of the processes of destabilization of particles of impurities and their aggregation.

Table 2: Comparison of the performance efficiency of different clarifiers installed at the municipal waterworks of the City of Bethlehem, OFS [1, 31]

| Source of raw water: | Mixture of Saulspoort Dam and Loch Athlone Dam waters |
| Raw water turbidity: | $C_0 = 102 \text{ NTU}$ |
| Date of plant operation: | November 12, 1978 |
| Aggregation agent: | Aluminium sulphate |
| Optimum dosage (Tu removal): | $D_{Al} = 60 \text{ mg.L}^{-1}$ |

<table>
<thead>
<tr>
<th>TYPE OF CLARIFIER</th>
<th>DOSSING RATE</th>
<th>UPFLOW VELOCITY</th>
<th>POINT OF MEASUREMENTS</th>
<th>TURBIDITY</th>
<th>DEGREE OF DESTABILISATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminium sulphate</td>
<td>SF-A110</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pretreator</td>
<td>60</td>
<td>0</td>
<td>1.5</td>
<td>Pre-aggregation chamber outlet</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hydraulic jump</td>
<td>102</td>
</tr>
</tbody>
</table>

NA - non-separable (non-aggregated) particles
PR - primary-aggregates
MI - micro-aggregates
MA - macro-aggregates
SF-A110 was dissolved in tap water

<table>
<thead>
<tr>
<th>TYPE OF CLARIFIER</th>
<th>POINT OF MEASUREMENT</th>
<th>TURBIDITY</th>
<th>TEST OF AGGREGATION</th>
<th>SEPARATION EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cc [NTU]</td>
<td>CcF [NTU]</td>
<td>MA [%]</td>
</tr>
<tr>
<td>Raw Water</td>
<td></td>
<td>102</td>
<td>54</td>
<td>-</td>
</tr>
<tr>
<td>Pre-agg. Chamber</td>
<td></td>
<td>102</td>
<td>4.9</td>
<td>75.5</td>
</tr>
<tr>
<td>Hydraulic Jump</td>
<td></td>
<td>102</td>
<td>4.0</td>
<td>17.6</td>
</tr>
<tr>
<td>Clarifier outlet</td>
<td></td>
<td>7.1</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Pre-agg. Chamber</td>
<td></td>
<td>102</td>
<td>4.9</td>
<td>75.5</td>
</tr>
<tr>
<td>Clarifier outlet</td>
<td></td>
<td>7.2</td>
<td>2.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Flocculator outlet</td>
<td></td>
<td>102</td>
<td>1.7</td>
<td>50.0</td>
</tr>
<tr>
<td>Clarifier outlet</td>
<td></td>
<td>7.0</td>
<td>1.4</td>
<td>2.6</td>
</tr>
</tbody>
</table>

φ – attained separation efficiency, ̅φ - attainable separation efficiency

Figure 22: Particle size-fraction distribution in water purified by different clarifier systems, calculated from turbidity

e) Large Capacity HR Clarifiers at the Saulspoort Waterworks

At the end of the seventies, the City Council of Bethlehem approved the installation of a 20 ML.d⁻¹ new waterworks to purify Saulspoort Dam water. The intended ultimate design capacity of the waterworks was 60 ML.d⁻¹, the design of the purification system should make provision for semi-automatic operation and allow for a plant overload of 50%.

The waterworks staff had gained a good knowledge and experience of the HRCT. The pilot HR clarifier proved to be efficient, simple and user friendly in operation and, unlike the old waterworks, allowed the process controllers (plant operators) to remain master of the plant at all times. Owing to this outstanding experience with the HRCT, the City Council decided to accept the concept of the HRCT for their new Saulspoort waterworks.
The design parameters of the HR clarifiers installed at the Saulspoort Waterworks (Figure 23) are as follows:

- **Design capacity**
  \[ Q = \ 10 \text{ ML.d}^{-1} = 417 \text{ m}^3.\text{h}^{-1} \]

- **Diameter**
  \[ D_C = 8650 \text{ mm} \]

- **Height of the clarifier**
  \[ H_C = 8200 \text{ mm} \]

- **Intensity of agitation in the Flocculator**
  \[ \overline{G} = \ 100 - 400 \text{ s}^{-1} \]

- **Total clarifier volume**
  \[ V_C = 315 \text{ m}^3 \]

- **Area of the sludge blanket at its separation level**
  \[ F_{SB} = 37.9 \text{ m}^2 \]

- **Upflow velocity at the sludge blanket level**
  \[ v_{UP} = 11.0 \text{ m.h}^{-1} \]

- **Separation area at the sludge thickener**
  \[ F_{ST} = 33.0 \text{ m}^2 \]

- **Retention time in the clarifier at design flow**
  \[ T_C = 45 \text{ min} \]

- **Average concentration of drained sludge**
  \[ C_S > 40 \text{ g.L}^{-1} \]

- The clarifier de-sludge pipe is fitted with a pneumatically operated butterfly valve. Operation of this valve can be initiated either manually or by a timer.

- The water softened for dissolution of OAA in 0.025 N NaOH electrolyte is prepared in situ.

- OAA is dissolved at a stock solution concentration 1.0 g.L\(^{-1}\) and the solution matures for 24 hours before its use.

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**Figure 23:** The Saulspoort waterworks – the HR clarifier, design capacity 10 ML.d-1

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f) **Performance Results**

The Saulspoort waterworks was put into operation in 1980 [32]. It was commissioned using both types of aggregation agent, namely aluminium sulphate and Floccotan. It should be pointed out that ferric chloride, because of greater raw water alkalinity is a more efficient coagulant than aluminium sulphate; however, aluminium sulphate was used during plant commissioning because ferric chloride was not available.

Commissioning of the waterworks was carried out under two sets of four runs, each set verifying certain aspects of the clarifier operation and performance. The operation with Floccotan was aimed at proving the importance of completion of aggregation in the Flocculator (\( \gamma = 1 \)) before the addition of OAA. During these trial runs the clarifiers operated at an upflow velocity \( v_{UP} = 6.5 \) and \( 12.0 \text{ m.h}^{-1} \) and \( \gamma = 0.34 \) to 1.0. The significance of the degree of aggregation (\( \gamma \)-value) achieved before the addition of OAA on the quality of purified water is best demonstrated by comparing the differences in the residual turbidity produced by the non-aggregated (non-separable) particles and measured at the outlet from the flash mixer \( C_{MF} \) and the outlet from the clarifier \( C_{CF} \). Evidently the lower the \( \gamma \)-value the poorer the purified water quality, while the hydraulic loading of the clarifier has no effect in this regard. The results obtained are shown in Table 3.
During the second set of commissioning runs with aluminium sulphate the clarifiers were operated at four different hydraulic loadings under optimized reaction conditions and at almost completed aggregation, \( \gamma \approx 1 \). These runs were aimed to verify the clarifier’s capability to operate safely and efficiently up to a 50% hydraulic overload, i.e. up to an upflow velocity \( v_{up} = 16.5 \text{ m.h}^{-1} \). The results obtained are shown in Table 4.

**Table 3:** The HR clarifiers commissioning results from the first set of tests [33]

<table>
<thead>
<tr>
<th>RUN No.</th>
<th>PERIOD OF OPERATION</th>
<th>UPFLOW VELOCITY ( v_{up} ) [m.h(^{-1})]</th>
<th>( \gamma )-VALUE</th>
<th>DOSING RATE FLOCCOTAN [mg.L(^{-1})]</th>
<th>RAW WATER ( C_0 ) NTU</th>
<th>FLASH MIXER ( C_{CF}^F ) NTU</th>
<th>CLARIFIER ( C_F ) NTU</th>
<th>TURBIDITY ( C_0F ) NTU</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4/9~15/10/80</td>
<td>6.5</td>
<td>1.00</td>
<td>12</td>
<td>0.05</td>
<td>45</td>
<td>24</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>15/10~21/12/80</td>
<td>12.0</td>
<td>0.85</td>
<td>12</td>
<td>0.05</td>
<td>36</td>
<td>23</td>
<td>2.1</td>
</tr>
<tr>
<td>3</td>
<td>21/12~10/2/81</td>
<td>12.0</td>
<td>0.34</td>
<td>20</td>
<td>0.10</td>
<td>115</td>
<td>42</td>
<td>5.8</td>
</tr>
<tr>
<td>4</td>
<td>10/2~20/2/81</td>
<td>12.0</td>
<td>0.75</td>
<td>20</td>
<td>0.10</td>
<td>115</td>
<td>42</td>
<td>2.8</td>
</tr>
</tbody>
</table>

The residual turbidity produced by non-aggregated particles and measured in the clarifier outlet was low with small differences irrespective of the upflow velocity. This is because, the \( \gamma \)-value was very close to 1 and the alum dosage to optimum. The performance results proved that the clarifier can consistently purify water to a good potable quality, in terms of the National Standard (SANS 241), even at the highest hydraulic loadings and shortest retention times providing \( \gamma = 1 \).

It can be concluded that the waterworks commissioning was very successful. The clarifier performance met all performance expectations and demonstrated that the HRCT can be the technology of the future.

At the beginning the waterworks was operated with Floccotan and a filtrate of sparkling clarity was produced, even at the highest flow, corresponding to an upflow velocity \( v_{up} = 16.5 \text{ m.h}^{-1} \) in the clarifier. During 1982 it was discovered by Van Steenderen [34] that Floccotan presents a potential health risk. Therefore, due to a dedicated check-up by Van Steenderen [35] (Table 5) it was discovered that the concentration of organohalogenens in the raw water increased in the filtrate from \( TOH_0 = 37 \text{ µg CHCl}_3.L^{-1} \) to \( TOH_F = 52 \text{ µg CHCl}_3.L^{-1} \). The \( TOH_F \) potential value increased even more from 878 to 1209 \( \text{µg CHCl}_3.L^{-1} \) as shown in Table 5. The \( TOH \) and \( TOH_F \) values in potable water should be lower and not exceeding that of the raw water. Therefore, Floccotan was immediately replaced with ferric chloride applied under optimized reaction conditions with regard to the monitored impurities [3].
Table 5: Secondary organic pollution of the purified water produced by natural OC (Floccotan) at the Saulspoort Waterworks (Van Steenderen) [35]

<table>
<thead>
<tr>
<th>Point of measurement</th>
<th>DOC [mg C L⁻¹]</th>
<th>TOH [μg CHCl₃ L⁻¹]</th>
<th>TOHp [μg CHCl₃ L⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw water</td>
<td>5.2</td>
<td>37</td>
<td>878</td>
</tr>
<tr>
<td>Flocculated water</td>
<td>4.8</td>
<td>-</td>
<td>1211</td>
</tr>
<tr>
<td>Filtrate</td>
<td>4.6</td>
<td>52</td>
<td>1209</td>
</tr>
</tbody>
</table>

Regrettably based on the advice of an organic coagulant supplier and without receiving any technological justification and proof that the water would not be purified to a poorer quality, the Municipality replaced ferric chloride with organic coagulant L-100 (assumed to be Poly DADMAC). Appraisal of treatability of the raw water attainable with ferric chloride and L-100 is shown in Table 6.

Table 6: Coagulation efficiency and treatability of the Saulspoort Dam water attained by optimized dosages of FeCl₃ and L-100 (organic coagulant) [36]

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw water at dosing point of FeCl₃</td>
<td>7.85</td>
<td>66</td>
<td>33</td>
<td>5.93</td>
<td>5.34</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L-100</td>
<td>7.95</td>
<td>74</td>
<td>38</td>
<td>5.8</td>
<td>0.25</td>
<td>0.18</td>
<td>1.45</td>
<td>1.40</td>
<td>0.02</td>
</tr>
<tr>
<td>Water purified by FeCl₃</td>
<td>100</td>
<td>5.8</td>
<td>0.25</td>
<td>0.18</td>
<td>1.45</td>
<td>1.40</td>
<td>0.02</td>
<td>0.996</td>
<td>0.755</td>
</tr>
<tr>
<td>L-100</td>
<td>1.5</td>
<td>7.92</td>
<td>3.0</td>
<td>1.6</td>
<td>4.48</td>
<td>4.41</td>
<td>-</td>
<td>0.959</td>
<td>0.275</td>
</tr>
</tbody>
</table>

It is evident from the comparison of the values of the degree of destabilization δ (coagulation efficiency) and the quality of purified water that L-100 is not an equivalent replacement for ferric chloride. This is because the efficiency of organic pollution removal is extremely poor and L-100 cannot purify water to the wholesome potable quality suitable for a lifelong consumption.

Due to the influx of people from the Kingdom of Lesotho at the end of the eighties, the waterworks operated up to a 50% hydraulic overload for about 5 years. During this time the clarifiers were operating between \( \nu_{up} = 11.0 \) and 16.5 \( \text{m.h}^{-1} \) until 1993, when the waterworks was extended to the present capacity of 40 ML.d⁻¹.

g) Mechanical Dewatering of the HR Clarifier Sludge

The suitability of sludge produced by the HR clarifiers for mechanical dewatering by centrifugation was investigated (Figures 24, 25). The tests were carried out with a Sharples PM 30000 Polymizer centrifuge in March 1981. The clarifier sludge was produced from raw water having a turbidity \( C_0 = 115 \text{ NTU} \) using Floccotan as coagulant under the IHDS process at \( \overline{G} = 200 \text{ s}^{-1} \) followed by the POA process with SF-A110 at a dosage \( D_{OAA} = 0.07 \text{ mg.L}^{-1} \). The concentration of sludge discharged from the clarifier was about 40 g.L⁻¹ (4.0 %).
The polymer LT-26 (a low toxicity grade recommended by Allied Colloids) was used to condition the clarifier sludge; it was dissolved in 0.025 N NaOH electrolyte. The concentration of the LT-26 solution was 1.0 g.L\(^{-1}\). The optimum feed rate of sludge to the centrifuge was established at 5.4 m\(^3\).h\(^{-1}\). The centrifuge operated at a bowl speed of 3150 RPM and a scroll differential speed of 8.2 RPM [37]. The solids content in the sludge discharged from the centrifuge, and the solids concentration in the liquid discharged from the centrifuge, were measured.

Two tests using different LT-26 dosages were carried out. In both cases, sludge of spadeable consistency were discharged from the centrifuge. At LT-26 dosage \(D_{OAA} = 0.68\) kg/tss the discharged sludge contained 34.4% w/v dry solids and the liquid discharged contained 120 mg SS.L\(^{-1}\). When the LT-26 dosage was reduced to \(D_{OAA} = 0.37\) kg/tss, the sludge discharged was less thick, nevertheless contained 31.2% dry solids and the liquid discharged was tinged brown containing 370 mg SS.L\(^{-1}\) [37]. This excellent economic dewatering properties of the clarifier sludge is yet another significant benefit of the HRCT.

h) Filterability of OAA Formed Agglomerates

The agglomeration of aggregates and deep-bed filtration are interrelated processes as the effectiveness of filtration is determined by the properties of the suspension formed in the preceding processes. However, the properties of agglomerates that are favorable for effective sedimentation may not be the most suitable for economic filtration and vice versa [38].

The purpose of agglomeration is not only the formation of a rapidly settleable suspension but also the formation of a suspension that is effectively and economically filterable to achieve long filtration cycles.

The filterability of the OAA formed agglomerates could not be investigated under the pilot HR clarifier operation. This could only be established during the operation of the Saulspoort waterworks. Similarly, the rise rate of filter headloss resulting from OAA application could not be assessed at the design stage. Therefore, an operational water height of 1500 mm above the filter bed was designed to produce an adequate safety margin for the operational pressure head to prevent operation under sub-atmospheric pressure conditions. Under these conditions the length of filtration cycle was longer than seven days. For hygienic reasons however, the length of filtration cycle was limited to a maximum of 72 hours. At the end of the reduced cycle the filter headloss did not exceed 1000 mm and on average it was below 600 mm.

i) The Saulspoort Waterworks

The remarkable benefit of the HRCT is the major reduction in the footprint and compact layout of the waterworks compared to traditional designs. It efficiently solved operational problems such as the elimination of well-known detrimental effect of the sun and wind on the performance stability of the clarifiers as well as the harsh climatic conditions that exist at the waterworks site, by the installation of a fully roofed-over waterworks (Figure 26). Further benefits resulting from the roofed-over plant are steady ambient conditions for the operation of the plant and equipment and for a pleasant working environment.

Another essential component of this waterworks is the inclusion of staff housing for the operating personnel. This feature together with the simple operation and effective functioning of the waterworks are the reasons for an almost non-existent staff turnover.

The Saulspoort waterworks (Figure 26) consists of three Buildings attached and mutually interconnected, namely:

- Administration and Operation Building,
- Technology Building,
- Pump Building.

The Administration and Operation Building is sized to service the ultimate waterworks capacity of 60 ML.d\(^{-1}\). Buildings of Technology and Pumps are...
designed to consist of three modules of 20 ML.d\(^{-1}\) capacity each.

**Figure 26:** The Saulspoort waterworks

- **(a)** Technology Building (18 x 36 m) combined with Pumps Building (6 x 18 m) create one module,
- **(b)** Side view of Administration and Operation Building and Building of Technology, one modulus capacity 20 ML.d\(^{-1}\),
- **(c)** Building of Administration and Operation (9.6 x 42 m),
- **(d)** Buildings of Technology and Pumps enlarged to two modules – capacity 40 ML.d\(^{-1}\).

The Technology Building accommodates raw water flow measurement, hydraulic flash mixer, flow division box, two HR clarifiers and the filtration plant. The filtration plants in both modules consists of four dual media rapid gravity filters. The filters are designed for a filtration velocity \(v_F = 10\) m.h\(^{-1}\); filter media consist of filter sand \(d_{50S}=0.9\) mm and height \(L_S=600\) mm and hydroantrazite \(d_{50A}=1.6\) mm and height \(L_A=300\) mm.

Operation of the filtration plant proved that a low concentration of suspension, conditioned with a small OAA dosage, entering the filters does not adversely affect the length of filtration cycles. However, the length of filtration cycles is affected by the efficiency of filter backwashing (the intensity of air scour and water backwash should be based on the grain size of the filter medium), and proper filter geometry, which are often ignored in the filter design.

The benefit of HRCT concerning the reduction of capital costs is evident from the reduced waterworks footprint.

**VIII. P-Clarifier Recovering Water from Eutrophic Sludge**

The City of Salisbury, Rhodesia (now the City of Harare, Zimbabwe) operated the Hunyani waterworks. This waterworks purifies water from the Hunyani dam. The Hunyani dam water is highly eutrophic and of low turbidity; for most of the time it seldom exceeds 15 NTU.

This raw water was purified in Pulsator clarifiers. These are vertical flow sludge blanket clarifiers. Pulsators were designed to operate at an upflow velocity \(v_{UP}=2.5\) m.h\(^{-1}\). Aluminium sulphate was used as aggregation agent. The maximum sludge concentration in the Pulsator sludge blanket did not exceed 1500 mg SS.L\(^{-1}\), and its performance was very unstable. Stabilization of the plant performance required up to 50% of the inlet flow to the Pulsators to be drained. In order to maintain the required waterworks capacity, the water contained in the clarifier sludge had to be recovered and delivered to filtration. For this reason the municipality issued a tender for the installation of a plant that would recover 70% of the water from the drained Pulsator sludge; the maximum concentration of the
suspended solids permitted in the recovered water was 25 mg SS.L⁻¹.

For this project, a 13.0 m diameter P-Clarifier sized for an upflow velocity of \( v_{UP} = 3.4 \) m.h⁻¹ was proposed and installed by E L Bateman Ltd. The dewatering process was based on the POA of the Pulsator sludge; the SF-A110 was used as the OAA. It was anticipated that OAA dosage would not exceed \( D_{OAA} = 1.5 \) mg.L⁻¹. Obviously, the actual OAA dosage had to be determined by the quality and the concentration of sludge entering the P-Clarifier and the required SS content at its outlet.

The P-Clarifier performed as follows [40]:

- **Capacity**
- Concentration of suspended solids at the inlet to P-Clarifier varied between
  - Average SF-A110 dosage
  - Upflow velocity
  - Average water recovery
  - Residual suspended solids in the recovered water
  - The content of SS in the P-Clarifier underflow

The storage time of the Pulsator sludge before its delivery to the P-Clarifier had to be very short due to its tendency to become septic.

The P-Clarifier proved capable dewatering the highly eutrophic sludge effectively in a simple and reliable operation. During its service life the volume of the Pulsator’s sludge gradually increased as the waterworks capacity expanded. Owing to that the P-Clarifier was finally running successfully at about three times its design capacity [39].

**IX. P-Clarifier Desilting Underground Gold Mine Water**

A pilot P-Clarifier was installed to test its efficiency for removing the high content of suspended solids from the underground mine water before pumping to the surface. Because this clarifier and the OAA dissolving and dosing plant would be installed underground next to the sedimentation system to reduce pumping cost, required the smallest footprint for this system.

The P-Clarifier was operated from 1976 to 1993, when it was taken out of service [39]. The results below were obtained during the acceptance testing carried out continuously at the maximum rated capacity \( Q = 10 \) ML.d⁻¹ during March 2 to 9, 1979. The SF-A110 stock solution of a concentration \( C_{OAA} = 1.0 \) g.L⁻¹ was prepared in 0.025 N NaOH electrolyte prepared from soft water. The OAA stock solution was matured for a minimum of 12 hours before its use.

\[
\begin{align*}
Q & = 10 \text{ ML.d}^{-1} \\
SS_{in} & = 400 - 1090 \text{ mg.L}^{-1} \\
\text{average } SS_{in} & = 860 \text{ mg.L}^{-1} \\
D_{OAA} & = 0.5 \text{ mg.L}^{-1} \\
v_{UP} & = 3.4 \text{ m.h}^{-1} \\
R & = 82\% \\
SS_{out} & \leq 4.0 \text{ mg.L}^{-1} \\
SS_{s} & = 2.42 - 4.08 \text{ g.L}^{-1}
\end{align*}
\]

The pilot P-Clarifier (600 mm diameter) was installed at No. 10 Shaft, Vaal Reefs Gold Mine and was operated at an upflow velocity \( v_{S} = 34.4 \text{ m.h}^{-1} \) (Figure 27). The content of suspended solids at the inlet to the mine water before pumping to the surface. Because this clarifier and the OAA dissolving and dosing plant would be installed underground next to the sedimentation system to reduce pumping cost, required the smallest footprint for this system.

**Figure 27:** The pilot P-Thickener dewatering underground mine water
P-Clarifier varied up to 20,000 mg.L\(^{-1}\). The OAA (N351) was dissolved in 0.025 N NaOH electrolyte at a concentration of 0.5 g.L\(^{-1}\). The flow through the plant was by gravity and varied considerably as it depended on the pumping arrangement from the mine; likewise concentration of suspended solids in the mine water varied considerably. At a \(C_0 = 5,000 \text{ mg SS.L}^{-1}\), \(D_{OAA} = 1.5 \text{ mg L}^{-1}\) and an upflow velocity \(v_s = 34.4 \text{ m.h}^{-1}\) the content of suspended solids at the P-Clarifier outlet was \(C_C < 20 \text{ mg L}^{-1}\).

A significant benefit of the P-Clarifier design is its ability to effectively float, collect and remove oil from the underground water at the top of the agglomeration compartment.

**Important Notice**

The great potential of HRCT evident from the presented results may probably not be duplicated in full extent as shown in this article. The reason is that the water soluble polymers used in the operation of High Rate Clarifiers were Superflocs provided by Cyanamid Co. of USA which no longer exists. Unfortunately, these Superflocs in the quality provided by Cyanamid Co. are no longer available. We believe the USA Cytec Co. manufactured the Superflocs for Cyanamid Co. and the Cytec Co. was acquired by Kemira Water Solutions, Inc. Based on our experience the polymers now supplied as Superflocs are remarkably of a poorer quality differing from the quality originally provided by Cyanamid Co. as day and night. If Kemira Water Solutions is the manufacturer / supplier of Superflocs they should return the Superflocs to their original quality. If they are not capable of doing it then they should supply the polymers of present-day quality under a different name to prevent any adverse and misleading information to their users.

**X. Conclusions**

1. A new water purification technology, the High Rate Clarification Technology, significantly accelerates the formation of flocculent suspension and its gravity separation never achieved before. This technology consists of two processes, namely the Inline High Density Suspension formation process, which takes place under a very high agitation intensity (\(\bar{G} >> 50 \text{ s}^{-1}\)) until the aggregation is completed followed by the Post-Orthokinetic Agglomeration process under which the dense micro-aggregates are agglomerated to large, heavy and rapidly settling agglomerates utilizing water soluble anionic or non-ionic polymers.

2. It was proven that the customary method of application of the water soluble polymers as coagulation and/or flocculant aids results in an impairment of the quality of purified water and the performance of rapid gravity filters. In addition, it does not form the most rapidly settling flocculent suspension. Therefore, this is not the most effective method for the use of water soluble polymers. The optimum method for the use off anionic and non-ionic polymers is when they are applied as agglomeration agents and not as coagulation or flocculation aids, which is present common practice. The agglomeration capability of anionic and non-ionic polymers is influenced by the physical-chemical conditions under which they are dissolved and their solution applied.

3. Degree of aggregation \(\gamma\) has been developed as a simple tool for assessing the level of aggregation reached at the point of addition of anionic or non-ionic polymers. The optimum is that at which aggregation is completed, \(\gamma = 1\); the \(\bar{G} T_o\) value used for calculation of \(\gamma\) value is aggregation agent dependent.

4. Two different types of clarifiers incorporating principles of the HRCT were developed:
   
   a) HR clarifier, a fully fluidized sludge blanket type, incorporating flocculation, sludge blanket, clarified water and sludge thickening compartments,
   
   b) P-clarifier, a circular, horizontal flow, sludge scraper free, high rate sedimentation type clarifier, incorporating the following compartments: flocculation, sedimentation, clarified water and sludge accumulation / thickening compartments; when it should operate as a high rate clarifier the function of the internal Flocculator is changed to the POA process and the Flocculator is installed externally next to the P-Clarifier.

5. A 3.0 m diameter HR clarifier was continuously operated by waterworks staff for a period of 7 years. Experience gained with the operation of this pilot plant can be summarized as follows:
   
   a) The purified water produced was filtered with waters discharged from three Clariflocculators installed at the waterworks. On average this pilot HR clarifier purified more than 1500 m\(^3\).d\(^{-1}\) of dam water and this water was used to cover the waterworks shortfall capacity.
   
   b) The highest operational flow rate of 2877 m\(^3\).d\(^{-1}\) corresponds to an upflow velocity at the sludge blanket level of 25.5 m.h\(^{-1}\) (83.66 ft.h\(^{-1}\)) and total retention time in the clarifier of 11.9 minutes. The highest concentration of sludge discharged from the clarifier was 73.05 g.L\(^{-1}\) (7.305 %). This indicates the significant positive effect of high intensity agitation on the density of formed flocculent suspension.
   
   c) The operation pilot HR clarifier proved to be very efficient, simple and user friendly and, unlike the old waterworks, allowed the process controller (plant operator) to remain master of the plant at all times.
d) Owing to the outstanding experience with the HRCT, the City Council decided to accept the HRCT and the HR Clarifiers for their new Saulspoort waterworks.

6. Two 10 ML.d⁻¹ capacity HR clarifiers were initially installed and about 13 years later another two HR clarifiers were installed. The experience gained with operation of this waterworks can be summarized as follows:

a) The HR clarifiers were designed for an upflow velocity of 11.0 m.h⁻¹ and retention time of 45 mins. However, they were successfully operated for 6 years at an upflow velocity between 11.0 and 16.5 m/h⁻¹, retention time in the clarifier between 45 and 30 minutes and consistently produced a very good quality purified water, when a hydrolyzing coagulant was used. The use of organic coagulants proved they are not an equivalent replacement for the hydrolyzing coagulants.

b) The operation of the waterworks also proved, the best purified water quality is produced when the degree of aggregation γ = 1 before addition of OAA.

c) The HR clarifiers sludge can very effectively and economically be dewatered to spadeable consistency by centrifugation.

d) The low dosages of OAA applied to the POA process did not produce any filterability problems because the filter media grading and filter backwashing system were appropriately designed.

7. A 10 ML.d⁻¹ P-clarifier designed for POA process was installed for the recovery of water from the Pulsator clarifier sludge; the Pulsators purified highly eutrophic dam water. The experience gained with this installation is summarized as follows:

a) The employer requested to recover at least 70% of water to contain less than 20 mg SS.L⁻¹ as the recovered water is delivered to filtration. The P-clarifier was successfully recovering 82% of water containing less than 4 mg SS.L⁻¹.

b) Over the years the P-clarifier flow increased about three times. It was taken out of service after some 25 years of operation.

8. A small pilot P-clarifier designed for desilting of the gold mine underground water was tested. The underground water containing up to about 20,000 mg SS.L⁻¹ was pumped to surface. Outstanding performance results were obtained. The underground water containing about 5 000 mg SS.L⁻¹ was desilted to contain less than 20 mg SS.L⁻¹ at an OAA dosage D₀AA = 1.5 mg.L⁻¹. Another significant benefit of the P-clarifier is its ability to float, collect and remove oil from the desilted water at the top of the agglomeration compartment.

Acknowledgement

The authors wish to gratefully acknowledge:

1. The Rand Water Board (RWB) of Johannesburg, South Africa, for allowing Mr. Polasek
   a) To continue testing a great variety of different polymers and thus contributing to the development of the POA method,
   b) To Dr R. Wells for convincing RWB management to install the first 3 m diameter pilot HR clarifier.

2. The Edw. L. Bateman Ltd:
   a) For installation of the second 3 m diameter pilot HR clarifier,
   b) For trusting Mr. Polasek with his proposal of using the P-Clarifier for a very delicate application of recovery of water from highly eutrophic sludge.

3. The City of Bethlehem for acceptance of the HRC technology in their new Saulspoort waterworks. In addition, the authors wish to extend their gratitude to the waterworks superintendent Mr W. Coleske and his staff for operating the pilot HR clarifier so successfully that the confidence in the HRC technology was gained and enabled the municipal authorities to issue permission for its implementation in the new Saulspoort waterworks.

4. The City of Salisbury, Rhodesia (now the City of Harare, Zimbabwe) for accepting the P-Clarifier for dewatering the eutrophic sludge from the Pulsator clarifiers installed at their Hunyani waterworks and its staff for the most successful operation of this plant.

Dedication

This article is dedicated to:

- The memory of our dear friend and colleague Dr Silvestr Mutl of the Institute for Hydrodynamics of the Czech Academy of Sciences who developed, among others, the Test of Aggregation which is an indispensable tool for the evaluation of aggregation efficiency as well as the performance efficiency of waterworks. Dr Mutl also contributed, through his knowledge and laboratory investigations carried out with his team of doctoral students, to the explanation of certain characteristics of the micro-aggregates formed under high agitation intensity. Some of these findings were subsequently included in the PhD thesis of Martin Pivokonsky.

- The memory of our dear friend and colleague Dipl. Ing. Arch. Vladimir Selzer who did the architectural design of the Saulspoort waterworks.

- all open-minded water purification specialists and waterworks operators.
Abreviations
BT - Blind test
COD\textsubscript{Mn} - Chemical oxygen demand determined by oxidation of the organic matter in a boiling mixture of potassium permanganate (KMnO\textsubscript{4}) and sulphuric acid
CSAV - Czechoslovak Academy of Sciences
DOC - Dissolved organic carbon
HR clarifier - High Rate sludge blanket clarifier
HRCT - High Rate Clarification Technology
IHDS - Inline High Density Suspension formation process
MA - Macro-aggregates
Me - Cation of hydrolyzing coagulant
MI - Micro-aggregates
NA - Non-aggregated, non-separable particles of impurities
NOM - Natural organic matter determined
NTU - Nephelometric turbidity unit
OAA - Organic agglomeration agent (anionic or non-ionic water-soluble polymer)
POA - Post-orthokinetic agglomeration process
PR - Primary aggregates
SS - Suspended solids
TOC - Total organic carbon
Tu - Turbidity

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Quantification of the influence of agitation intensity and time on the properties of formed aggregates. J. Hydrol. Hydromech, 59, 3, 196–205.


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Response Spectra Study of High Rise Structure with RC Shear Wall by Considering Lateral Loads and Storey Stiffness

By Mahdi Hosseini
Nanjing Forestry University

Abstract- The present study aims at evaluation of the behavior of a high rise structure with dual system for estimation of structural response lateral loads and storey stiffness has been studied. To meet this objective, G+29 storey building with C shape, Box shape, E shape, I shape and plus shape of RC shear wall, at the center in concrete frame structure with fixed support conditions under different types of soil for high earthquake zone are analyzed by dynamic analysis in ETABS software. It was found that the building with box shape shear walls provided at the center core showed very significant performance in terms of lateral loads and storey stiffness. It was found that the behavior of new shape (plus shape) of shear wall is similar to I and box shape.

For severe lateral loads caused by wind load and or earthquake load, the RC shear wall is obvious.

Keywords: dynamic analysis, structural response, soil conditions, high earthquake zone, ETABS software.

GJRE-E Classification: LCC: TA658.44
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For severe lateral loads caused by wind load or earthquake load, the RC shear wall is obvious.

Keywords: dynamic analysis, structural response, soil conditions, high earthquake zone, ETABS software.

I. INTRODUCTION

Shear wall is a structural element used to resist lateral/horizontal/shear forces parallel to the plane of the wall by:

• Cantilever action for slender walls where the bending deformation is dominant.
• Truss action for squat/short walls where the shear deformation is dominant.

Shear walls resist two types of forces: shear forces and uplift forces. Connections to the Structure above transfer horizontal forces to the shear wall. This transfer creates shear forces throughout the height of the wall between the top and bottom shear wall connections. The strength of the lumber, sheathing and fasteners must resist these shear forces or the wall will tear or “shear” apart uplift forces exist on shear walls because the horizontal forces are applied to the top of the wall. These uplift forces try to lift up one end of the wall and push the other end down. In some cases, the uplift force is large enough to tip the wall over. Uplift forces are greater on tall short walls and less on low long walls. Bearing walls have less uplift than non-bearing walls because gravity loads on shear walls help them resist uplift. Shear walls need holdown devices at each End when the gravity loads cannot resist all of the uplift. The holdown device then provides the necessary uplift resistance.

a) Site Selection

The seismic motion that reaches a structure on the surface of the earth is influenced by local soil conditions. The subsurface soil layers underlying the building foundation may amplify the response of the building to earthquake motions originating in the bedrock.

For soft soils the earthquake vibrations can be significantly amplified and hence the shaking of structures sited on soft soils can be much greater than for structures sited on hard soils. Hence the appropriate soil investigation should be carried out to establish the allowable bearing capacity and nature of soil. The choice of a site for a building from the failure prevention point of view is mainly concerned with the stability of the ground. The very loose sands or sensitive clays are liable to be destroyed by the earthquake, so much as to lose their original structure and thereby undergo compaction. This would result in large unequal settlements and damage the building. If the loose cohesion less soils are saturated with water they are likely to lose their shear resistance altogether during ground shaking. This leads to liquefaction. Although such soils can be compacted, for small buildings the operation may be too costly and the sites having these soils are better avoided.

For large building complexes, such as housing developments, new colonies, etc. this factor should be thoroughly investigated and the site has to be selected appropriately. Therefore a site with sufficient bearing capacity and free from the above defects should be chosen and its drainage condition improved so that no water accumulates and saturates the ground especially close to the footing level.

b) Bearing Capacity of Foundation Soil

Three soil types are considered here:

I. Hard - Those soils, which have an allowable bearing capacity of more than 10t/m2.
II. Medium - Those soils, which have an allowable bearing capacity less than or equal to 10t/m2.
III. Soft - Those soils, which are liable to large differential settlement or liquefaction during an earthquake.

II. Methodology

a) Dynamic Analysis

Dynamic analysis shall be performed to obtain the design seismic force, and its distribution in different levels along the height of the building, and in the various lateral load resisting element, for the following buildings:

Regular buildings: Those greater than 40m in height in zones IV and V, those greater than 90m in height in zone II and III.

Irregular Buildings: All framed buildings higher than 12m in zones IV and V, and those greater than 40m in height in zones II and III.

The analysis of model for dynamic analysis of buildings with unusual configuration should be such that it adequately models the types of irregularities present in the building configuration. Buildings with plan irregularities, as defined in IS code: 1893-2002 cannot be modeled for dynamic analysis.

Dynamic analysis may be performed either by the TIME HISTORY METHOD or by the RESPONSE SPECTRUM METHOD.

b) Response Spectrum Method

The word spectrum in engineering conveys the idea that the response of buildings having a broad range of periods is summarized in a single graph. This method shall be performed using the design spectrum specified in code or by a site-specific design spectrum for a structure prepared at a project site. The values of damping for building may be taken as 2 and 5 percent of the critical, for the purposes of dynamic of steel and reinforce concrete buildings, respectively. For most buildings, inelastic response can be expected to occur during a major earthquake, implying that an inelastic analysis is more proper for design. However, in spite of the availability of nonlinear inelastic programs, they are not used in typical design practice because:

1. Their proper use requires knowledge of their inner workings and theories, design criteria, and
2. Result produced are difficult to interpret and apply to traditional design criteria, and
3. The necessary computations are expensive.

Therefore, analysis in practice typically use linear elastic procedures based on the response spectrum method. The response spectrum analysis is the preferred method because it is easier to use.

c) Response Spectrum Analysis

This method is also known as modal method or mode superposition method. It is based on the idea that the response of a building is the superposition of the responses of individual modes of vibration, each mode responding with its own particular deformed shape, its own frequency, and with its own modal damping.

According to IS-1893(Part-I):2002, high rise and irregular buildings must be analyzed by response spectrum method using design spectra. There are significant computational advantages using response spectra method of seismic analysis for prediction of displacements and member forces in structural systems. The method involves only the calculation of the maximum values of the displacements and member forces in each mode using smooth spectra that are the average of several earthquake motions. Sufficient modes to capture such that at least 90% of the participating mass of the building (in each of two orthogonal principle horizontal directions) have to be considered for the analysis. The analysis is performed to determine the base shear for each mode using given building characteristics and ground motion spectra. And then the storey forces, accelerations, and displacements are calculated for each mode, and are combined statistically using the SRSS combination. However, in this method, the design base shear \( V_b \) shall be compared with a base shear \( V_b \) calculated using a fundamental period \( T \). If it is less than response quantities are (for example member forces, displacements, storey forces, storey shears and base reactions) multiplied by \( V_b \). Response spectrum method of analysis shall be performed using design spectrum. In case design spectrum is specifically prepared for a structure at a particular project site, the same may be used for design at the discretion of the project authorities.

III. Modeling of Building

a) Details of the Building

A symmetrical building of plan 38.5m X 35.5m located with location in zone V, India is considered. Four bays of length 7.5m & one bays of length 8.5m along X-direction and Four bays of length 7.5m & one bays of length 5.5m along Y-direction are provided. Shear Wall is provided at the center core of building model.

Structure 1: G+29 storey building with I-shape shear wall at the center of structure.

Structure 2: G+29 storey building with box shape shear wall at the center of structure.

Structure 3: G+29 storey building with C-shape shear wall at the center of structure.

Structure 4: G+29 storey building with E-shape shear wall at the center of structure.

Structure 5: G+29 storey building with L-shape shear wall at the center of structure.

b) Load Combinations

As per IS 1893 (Part 1): 2002 Clause no. 6.3.1.2, the following load cases have to be considered for analysis.
1.5 (DL + IL)
1.2 (DL + IL ± EL)
1.5 (DL ± EL)
0.9 DL ± 1.5 EL

Earthquake load must be considered for +X, -X, +Y and –Y directions.

Table 1: Details of the Building

<table>
<thead>
<tr>
<th>Building Parameters</th>
<th>Details</th>
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<tbody>
<tr>
<td>Type of frame</td>
<td>Special RC moment resisting frame fixed at the base</td>
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<td>Building plan</td>
<td>38.5m X 35.5m</td>
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<tr>
<td>Number of storeys</td>
<td>30</td>
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<td>Floor height</td>
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<td>Depth of Slab</td>
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<tr>
<td>Size of beam</td>
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<td>Size of column (exterior)</td>
<td>(1250×1250) mm up to story five</td>
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<tr>
<td>Size of column (interior)</td>
<td>(900×900) mm Above story five</td>
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<td>Spacing between frames</td>
<td>7.5-8.5 m along x - direction</td>
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<tr>
<td></td>
<td>7.5-5.5 m along y - direction</td>
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<td>Floor finish</td>
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<td>Soil Type III</td>
<td>Hard Soil</td>
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<td>Damping of structure</td>
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Figure 1: Plan of the Structure 1

Figure 2: 3D view showing shear wall location for Structure 1

Figure 3: Plan of the Structure 2

Figure 4: 3D view showing shear wall location for Structure 2
Figure 5: Plan of the Structure 3

Figure 6: 3D view showing shear wall location for Structure 3

Figure 7: Plan of the Structure 4

Figure 8: 3D view showing shear wall location for Structure 4
IV. Results and Discussions

Table 2: Lateral loads of structures in soft soil in X - direction with load cases EQXP\(^{+}\)kN\(^{-}\)

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<th>Story</th>
<th>Elevation (m)</th>
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<th>Structure -2</th>
<th>Structure -3</th>
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Graph 1: Lateral loads of structures in soft soil in X - direction with load cases EQXP

Table 3: Lateral loads of Structures in Medium Soil in X - Direction with load cases EQXP"kN"
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**Graph 2**: Lateral loads of structures in medium soil in X - direction with load cases EQXP

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Graph 3: Lateral loads of structures in hard soil in X - direction with load cases EQXP

Table 5: Lateral loads of structures in soft soil in Y - direction with load cases EQYP"kN"

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Graph 4: Lateral loads of structures in soft soil in Y-direction with load cases EQYP

Table 6: Lateral loads of structures in medium soil in Y-direction with load cases EQYP"kN"

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Graph 5: Lateral loads of structures in medium soil in Y - direction with load cases EQYP

Table 7: Lateral loads of structures in hard soil in Y - direction with load cases EQYP"kN"
### Graph 6: Lateral loads of structures in hard soil in Y - direction with load cases EQYP
### Table 8: Storey stiffness of structures in X - direction with load cases EQXP “kN/m”

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Table 9: Storey stiffness of structures in Y - direction with load cases EQYP “kN/m”

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a) **Discussion on Results**

When a structure is subjected to earthquake, it responds by vibrating. An example force can be resolved into three mutually perpendicular directions - two horizontal directions (X and Y directions) and the vertical direction (Z). This motion causes the structure to vibrate or shake in all three directions; the predominant direction of shaking is horizontal. All the structures are primarily designed for gravity loads - force equal to mass times gravity in the vertical direction. Because of the inherent factor used in the design specifications, most structures tend to be adequately protected against vertical shaking. Vertical acceleration should also be considered in structures with large spans those in which...
stability for design, or for overall stability analysis of structures. The basic intent of design theory for earthquake resistant structures is that buildings should be able to resist minor earthquakes without damage, resist moderate earthquakes without structural damage but with some non-structural damage. To avoid collapse during a major earthquake, Members must be ductile enough to absorb and dissipate energy by post elastic deformation. Redundancy in the structural system permits redistribution of internal forces in the event of the failure of key elements. When the primary element or system yields or fails, the lateral force can be redistributed to a secondary system to prevent progressive failure. The structures are supported on soil, most of the designers do not consider the soil structure interaction and its subsequent effect on structures during an earthquake. When a structure is subjected to an earthquake excitation, it interacts with the foundation and the soil, and thus changes the motion of the ground. This means that the movement of the whole ground-structure system is influenced by the type of soil as well as by the type of structure. Understanding of soil structure interaction will enable the designer to design structures that will behave better during an earthquake.

V. Conclusions

In this paper, reinforced concrete shear wall buildings were analyzed with the procedures laid out in IS codes. Seismic performance of building model is evaluated. In this study, regular shaped structures have been considered. Estimation of structural response was carried out for Dual frame system with shear wall structure.

From the above results and discussions, following conclusions can be drawn:

- Building with box shape shear walls provided at the center core showed better performance in term of storey stiffness and lateral loads.
- Provision of the shear wall, generally results in reducing the displacement because the shear wall increases the stiffness of the building.
- It is observed that the value of stiffness in X & Y-direction is same for all models with a different type of soil.
- The value of the lateral loads in x-direction for all models decreases with increase in storey level and also. The value of the lateral loads in x-direction for all models in soft soil is less compared with the structure in medium soil and hard soil, lateral loads in X-direction for all models in soft soil < Medium soil < hard soil.
- Percentage of lateral load for all three type of soil is same.
- For severe lateral loads caused by wind load and or earthquake load, the reinforced shear wall is obvious. Because, it produces less deflection and less bending moment in connecting beams under lateral loads than all others structural system.
- It is evident that shear walls which are provided from the foundation to the rooftop, are one of the excellent mean for providing earthquake resistant to multistory reinforced building with different type of soil.
- ETABS is the advanced software which is used for analysing any kind of building structures. By its fast and accuracy it can easily analyses buildings up to 40 floors. ETABS can analyse any building structure with pre-determined load conditions and load combinations for shear walls regarding IS codes.

Acknowledgments

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Conflict of Interest
The author declare no conflict of interest.

Data Availability Statement
All data generated or analysed during this study are included in this article.

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b) A summary, known as an abstract (less than 150 words), containing the major results and conclusions.
c) Up to 10 keywords that precisely identify the paper’s subject, purpose, and focus.
d) An introduction, giving fundamental background objectives.
e) Resources and techniques with sufficient complete experimental details (wherever possible by reference) to permit repetition, sources of information must be given, and numerical methods must be specified by reference.
f) Results which should be presented concisely by well-designed tables and figures.
g) Suitable statistical data should also be given.
h) All data must have been gathered with attention to numerical detail in the planning stage.

Design has been recognized to be essential to experiments for a considerable time, and the editor has decided that any paper that appears not to have adequate numerical treatments of the data will be returned unrefereed.

i) Discussion should cover implications and consequences and not just recapitulate the results; conclusions should also be summarized.
j) There should be brief acknowledgments.
k) There ought to be references in the conventional format. Global Journals recommends APA format.

Authors should carefully consider the preparation of papers to ensure that they communicate effectively. Papers are much more likely to be accepted if they are carefully designed and laid out, contain few or no errors, are summarizing, and follow instructions. They will also be published with much fewer delays than those that require much technical and editorial correction.

The Editorial Board reserves the right to make literary corrections and suggestions to improve brevity.
**Format Structure**

*It is necessary that authors take care in submitting a manuscript that is written in simple language and adheres to published guidelines.*

All manuscripts submitted to Global Journals should include:

**Title**

The title page must carry an informative title that reflects the content, a running title (less than 45 characters together with spaces), names of the authors and co-authors, and the place(s) where the work was carried out.

**Author details**

The full postal address of any related author(s) must be specified.

**Abstract**

The abstract is the foundation of the research paper. It should be clear and concise and must contain the objective of the paper and inferences drawn. It is advised to not include big mathematical equations or complicated jargon.

Many researchers searching for information online will use search engines such as Google, Yahoo or others. By optimizing your paper for search engines, you will amplify the chance of someone finding it. In turn, this will make it more likely to be viewed and cited in further works. Global Journals has compiled these guidelines to facilitate you to maximize the web-friendliness of the most public part of your paper.

**Keywords**

A major lynchpin of research work for the writing of research papers is the keyword search, which one will employ to find both library and internet resources. Up to eleven keywords or very brief phrases have to be given to help data retrieval, mining, and indexing.

One must be persistent and creative in using keywords. An effective keyword search requires a strategy: planning of a list of possible keywords and phrases to try.

Choice of the main keywords is the first tool of writing a research paper. Research paper writing is an art. Keyword search should be as strategic as possible.

One should start brainstorming lists of potential keywords before even beginning searching. Think about the most important concepts related to research work. Ask, “What words would a source have to include to be truly valuable in a research paper?” Then consider synonyms for the important words.

It may take the discovery of only one important paper to steer in the right keyword direction because, in most databases, the keywords under which a research paper is abstracted are listed with the paper.

**Numerical Methods**

Numerical methods used should be transparent and, where appropriate, supported by references.

**Abbreviations**

Authors must list all the abbreviations used in the paper at the end of the paper or in a separate table before using them.

**Formulas and equations**

Authors are advised to submit any mathematical equation using either MathJax, KaTeX, or LaTeX, or in a very high-quality image.

**Tables, Figures, and Figure Legends**

Tables: Tables should be cautiously designed, uncrowned, and include only essential data. Each must have an Arabic number, e.g., Table 4, a self-explanatory caption, and be on a separate sheet. Authors must submit tables in an editable format and not as images. References to these tables (if any) must be mentioned accurately.

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Figures

Figures are supposed to be submitted as separate files. Always include a citation in the text for each figure using Arabic numbers, e.g., Fig. 4. Artwork must be submitted online in vector electronic form or by emailing it.

Preparation of Electronic Figures for Publication

Although low-quality images are sufficient for review purposes, print publication requires high-quality images to prevent the final product being blurred or fuzzy. Submit (possibly by e-mail) EPS (line art) or TIFF (halftone/photographs) files only. MS PowerPoint and Word Graphics are unsuitable for printed pictures. Avoid using pixel-oriented software. Scans (TIFF only) should have a resolution of at least 350 dpi (halftone) or 700 to 1100 dpi (line drawings). Please give the data for figures in black and white or submit a Color Work Agreement form. EPS files must be saved with fonts embedded (and with a TIFF preview, if possible).

For scanned images, the scanning resolution at final image size ought to be as follows to ensure good reproduction: line art: >650 dpi; halftones (including gel photographs): >350 dpi; figures containing both halftone and line images: >650 dpi.

Color charges: Authors are advised to pay the full cost for the reproduction of their color artwork. Hence, please note that if there is color artwork in your manuscript when it is accepted for publication, we would require you to complete and return a Color Work Agreement form before your paper can be published. Also, you can email your editor to remove the color fee after acceptance of the paper.

Tips for Writing a Good Quality Engineering Research Paper

Techniques for writing a good quality engineering research paper:

1. Choosing the topic: In most cases, the topic is selected by the interests of the author, but it can also be suggested by the guides. You can have several topics, and then judge which you are most comfortable with. This may be done by asking several questions of yourself, like "Will I be able to carry out a search in this area? Will I find all necessary resources to accomplish the search? Will I be able to find all information in this field area?" If the answer to this type of question is "yes," then you ought to choose that topic. In most cases, you may have to conduct surveys and visit several places. Also, you might have to do a lot of work to find all the rises and falls of the various data on that subject. Sometimes, detailed information plays a vital role, instead of short information. Evaluators are human: The first thing to remember is that evaluators are also human beings. They are not only meant for rejecting a paper. They are here to evaluate your paper. So present your best aspect.

2. Think like evaluators: If you are in confusion or getting demotivated because your paper may not be accepted by the evaluators, then think, and try to evaluate your paper like an evaluator. Try to understand what an evaluator wants in your research paper, and you will automatically have your answer. Make blueprints of paper: The outline is the plan or framework that will help you to arrange your thoughts. It will make your paper logical. But remember that all points of your outline must be related to the topic you have chosen.

3. Ask your guides: If you are having any difficulty with your research, then do not hesitate to share your difficulty with your guide (if you have one). They will surely help you out and resolve your doubts. If you can't clarify what exactly you require for your work, then ask your supervisor to help you with an alternative. He or she might also provide you with a list of essential readings.

4. Use of computer is recommended: As you are doing research in the field of research engineering then this point is quite obvious. Use right software: Always use good quality software packages. If you are not capable of judging good software, then you can lose the quality of your paper unknowingly. There are various programs available to help you which you can get through the internet.

5. Use the internet for help: An excellent start for your paper is using Google. It is a wondrous search engine, where you can have your doubts resolved. You may also read some answers for the frequent question of how to write your research paper or find a model research paper. You can download books from the internet. If you have all the required books, place importance on reading, selecting, and analyzing the specified information. Then sketch out your research paper. Use big pictures: You may use encyclopedias like Wikipedia to get pictures with the best resolution. At Global Journals, you should strictly follow here.
6. **Bookmarks are useful:** When you read any book or magazine, you generally use bookmarks, right? It is a good habit which helps to not lose your continuity. You should always use bookmarks while searching on the internet also, which will make your search easier.

7. **Revise what you wrote:** When you write anything, always read it, summarize it, and then finalize it.

8. **Make every effort:** Make every effort to mention what you are going to write in your paper. That means always have a good start. Try to mention everything in the introduction—what is the need for a particular research paper. Polish your work with good writing skills and always give an evaluator what he wants. Make backups: When you are going to do any important thing like making a research paper, you should always have backup copies of it either on your computer or on paper. This protects you from losing any portion of your important data.

9. **Produce good diagrams of your own:** Always try to include good charts or diagrams in your paper to improve quality. Using several unnecessary diagrams will degrade the quality of your paper by creating a hodgepodge. So always try to include diagrams which were made by you to improve the readability of your paper. Use of direct quotes: When you do research relevant to literature, history, or current affairs, then use of quotes becomes essential, but if the study is relevant to science, use of quotes is not preferable.

10. **Use proper verb tense:** Use proper verb tenses in your paper. Use past tense to present those events that have happened. Use present tense to indicate events that are going on. Use future tense to indicate events that will happen in the future. Use of wrong tenses will confuse the evaluator. Avoid sentences that are incomplete.

11. **Pick a good study spot:** Always try to pick a spot for your research which is quiet. Not every spot is good for studying.

12. **Know what you know:** Always try to know what you know by making objectives, otherwise you will be confused and unable to achieve your target.

13. **Use good grammar:** Always use good grammar and words that will have a positive impact on the evaluator; use of good vocabulary does not mean using tough words which the evaluator has to find in a dictionary. Do not fragment sentences. Eliminate one-word sentences. Do not ever use a big word when a smaller one would suffice.

    Verbs have to be in agreement with their subjects. In a research paper, do not start sentences with conjunctions or finish them with prepositions. When writing formally, it is advisable to never split an infinitive because someone will (wrongly) complain. Avoid clichés like a disease. Always shun irritating alliteration. Use language which is simple and straightforward. Put together a neat summary.

14. **Arrangement of information:** Each section of the main body should start with an opening sentence, and there should be a changeover at the end of the section. Give only valid and powerful arguments for your topic. You may also maintain your arguments with records.

15. **Never start at the last minute:** Always allow enough time for research work. Leaving everything to the last minute will degrade your paper and spoil your work.

16. **Multitasking in research is not good:** Doing several things at the same time is a bad habit in the case of research activity. Research is an area where everything has a particular time slot. Divide your research work into parts, and do a particular part in a particular time slot.

17. **Never copy others’ work:** Never copy others’ work and give it your name because if the evaluator has seen it anywhere, you will be in trouble. Take proper rest and food: No matter how many hours you spend on your research activity, if you are not taking care of your health, then all your efforts will have been in vain. For quality research, take proper rest and food.

18. **Go to seminars:** Attend seminars if the topic is relevant to your research area. Utilize all your resources.

19. **Refresh your mind after intervals:** Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

20. **Think technically:** Always think technically. If anything happens, search for its reasons, benefits, and demerits. Think and then print: When you go to print your paper, check that tables are not split, headings are not detached from their descriptions, and page sequence is maintained.

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21. **Adding unnecessary information:** Do not add unnecessary information like "I have used MS Excel to draw graphs." Irrelevant and inappropriate material is superfluous. Foreign terminology and phrases are not apropos. One should never take a broad view. Analogy is like feathers on a snake. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Never oversimplify: When adding material to your research paper, never go for oversimplification; this will definitely irritate the evaluator. Be specific. Never use rhythmic redundancies. Contractions shouldn’t be used in a research paper. Comparisons are as terrible as clichés. Give up ampersands, abbreviations, and so on. Remove commas that are not necessary. Parenthetical words should be between brackets or commas. Understatement is always the best way to put forward earth-shaking thoughts. Give a detailed literary review.

22. **Report concluded results:** Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.

23. **Upon conclusion:** Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium through which your research is going to be in print for the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects of your research.

**Informal Guidelines of Research Paper Writing**

**Key points to remember:**

- Submit all work in its final form.
- Write your paper in the form which is presented in the guidelines using the template.
- Please note the criteria peer reviewers will use for grading the final paper.

**Final points:**

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

**The introduction:** This will be compiled from reference matter and reflect the design processes or outline of basis that directed you to make a study. As you carry out the process of study, the method and process section will be constructed like that. The results segment will show related statistics in nearly sequential order and direct reviewers to similar intellectual paths throughout the data that you gathered to carry out your study.

**The discussion section:**

This will provide understanding of the data and projections as to the implications of the results. The use of good quality references throughout the paper will give the effort trustworthiness by representing an alertness to prior workings.

Writing a research paper is not an easy job, no matter how trouble-free the actual research or concept. Practice, excellent preparation, and controlled record-keeping are the only means to make straightforward progression.

**General style:**

Specific editorial column necessities for compliance of a manuscript will always take over from directions in these general guidelines.

**To make a paper clear:** Adhere to recommended page limits.

**Mistakes to avoid:**

- Insertion of a title at the foot of a page with subsequent text on the next page.
- Separating a table, chart, or figure—confine each to a single page.
- Submitting a manuscript with pages out of sequence.
- In every section of your document, use standard writing style, including articles ("a" and "the").
- Keep paying attention to the topic of the paper.
• Use paragraphs to split each significant point (excluding the abstract).
• Align the primary line of each section.
• Present your points in sound order.
• Use present tense to report well-accepted matters.
• Use past tense to describe specific results.
• Do not use familiar wording; don't address the reviewer directly. Don't use slang or superlatives.
• Avoid use of extra pictures—include only those figures essential to presenting results.

Title page:

Choose a revealing title. It should be short and include the name(s) and address(es) of all authors. It should not have acronyms or abbreviations or exceed two printed lines.

Abstract: This summary should be two hundred words or less. It should clearly and briefly explain the key findings reported in the manuscript and must have precise statistics. It should not have acronyms or abbreviations. It should be logical in itself. Do not cite references at this point.

An abstract is a brief, distinct paragraph summary of finished work or work in development. In a minute or less, a reviewer can be taught the foundation behind the study, common approaches to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study with the subsequent elements in any summary. Try to limit the initial two items to no more than one line each.

Reason for writing the article—theory, overall issue, purpose.

• Fundamental goal.
• To-the-point depiction of the research.
• Consequences, including definite statistics—if the consequences are quantitative in nature, account for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- Single section and succinct.
- An outline of the job done is always written in past tense.
- Concentrate on shortening results—limit background information to a verdict or two.
- Exact spelling, clarity of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else.

Introduction:

The introduction should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- Explain the value (significance) of the study.
- Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- Briefly explain the study's tentative purpose and how it meets the declared objectives.
Approach:

Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done. Sort out your thoughts; manufacture one key point for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order, but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt to give the least amount of information that would permit another capable scientist to replicate your outcome, but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section.

When a technique is used that has been well-described in another section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show all particular resources and broad procedures so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step-by-step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

*Materials may be reported in part of a section or else they may be recognized along with your measures.*

Methods:

- Report the method and not the particulars of each process that engaged the same methodology.
- Describe the method entirely.
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures.
- Simplify—detail how procedures were completed, not how they were performed on a particular day.
- If well-known procedures were used, account for the procedure by name, possibly with a reference, and that’s all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer’s interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and every other part of the paper—avoid familiar lists, and use full sentences.

What to keep away from:

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings—save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part as entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.
Content:
- Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
- In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation of an exacting study.
- Explain results of control experiments and give remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or manuscript.

What to stay away from:
- Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
- Do not include raw data or intermediate calculations in a research manuscript.
- Do not present similar data more than once.
- A manuscript should complement any figures or tables, not duplicate information.
- Never confuse figures with tables—there is a difference.

Approach:
As always, use past tense when you submit your results, and put the whole thing in a reasonable order.

Put figures and tables, appropriately numbered, in order at the end of the report.

If you desire, you may place your figures and tables properly within the text of your results section.

Figures and tables:
If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:
The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an argument should be.

Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully described.

Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact, you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved the prospect, and let it drop at that. Make a decision as to whether each premise is supported or discarded or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."

Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work.
- You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
- Give details of all of your remarks as much as possible, focusing on mechanisms.
- Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
- One piece of research will not counter an overall question, so maintain the large picture in mind. Where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.
Approach:

When you refer to information, differentiate data generated by your own studies from other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

THE ADMINISTRATION RULES

Administration Rules to Be Strictly Followed before Submitting Your Research Paper to Global Journals Inc.

Please read the following rules and regulations carefully before submitting your research paper to Global Journals Inc. to avoid rejection.

Segment draft and final research paper: You have to strictly follow the template of a research paper, failing which your paper may get rejected. You are expected to write each part of the paper wholly on your own. The peer reviewers need to identify your own perspective of the concepts in your own terms. Please do not extract straight from any other source, and do not rephrase someone else's analysis. Do not allow anyone else to proofread your manuscript.

Written material: You may discuss this with your guides and key sources. Do not copy anyone else's paper, even if this is only imitation, otherwise it will be rejected on the grounds of plagiarism, which is illegal. Various methods to avoid plagiarism are strictly applied by us to every paper, and, if found guilty, you may be blacklisted, which could affect your career adversely. To guard yourself and others from possible illegal use, please do not permit anyone to use or even read your paper and file.
Please note that following table is only a Grading of "Paper Compilation" and not on "Performed/Stated Research" whose grading solely depends on Individual Assigned Peer Reviewer and Editorial Board Member. These can be available only on request and after decision of Paper. This report will be the property of Global Journals.

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